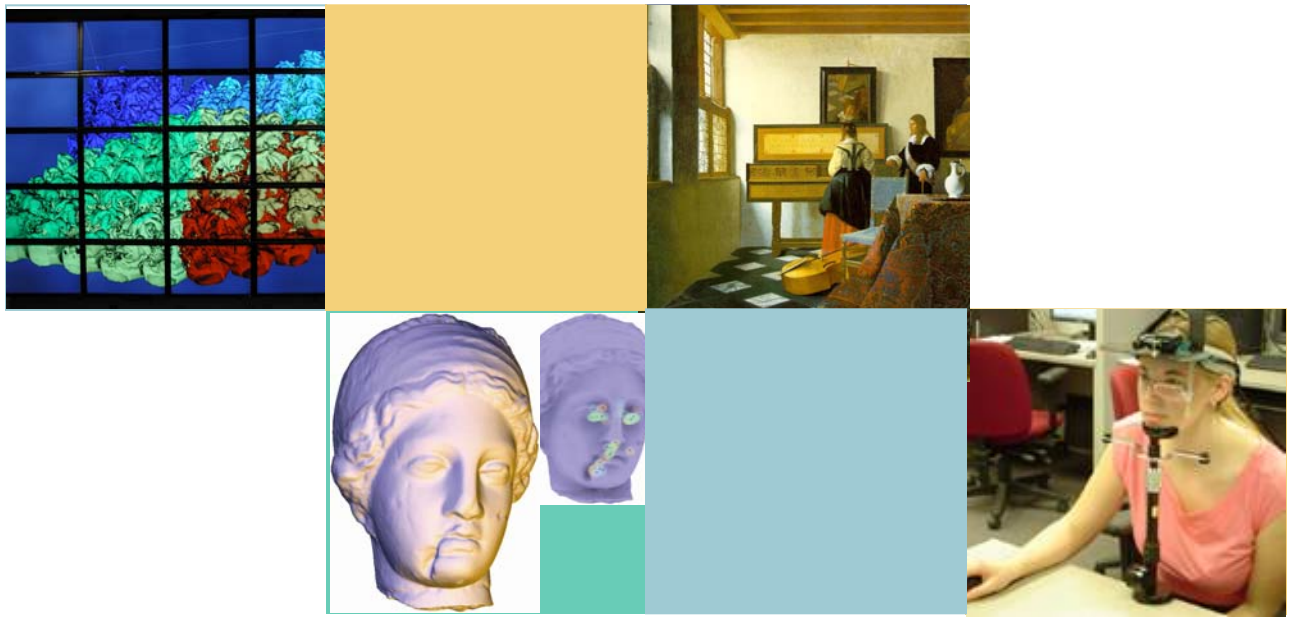
Salient Visualization



Amitabh Varshney

Department of Computer Science

University of Maryland at College Park

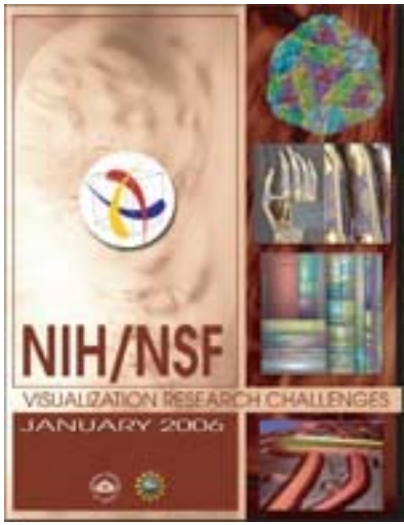
http://www.cs.umd.edu/~varshney

The Biggest Challenge of Our Era

Data and Information Overload

Data produced during 2003 – 2005 exceeds *all* of the previously created data by mankind

… and 90% of the new data is digital



Acquisition:

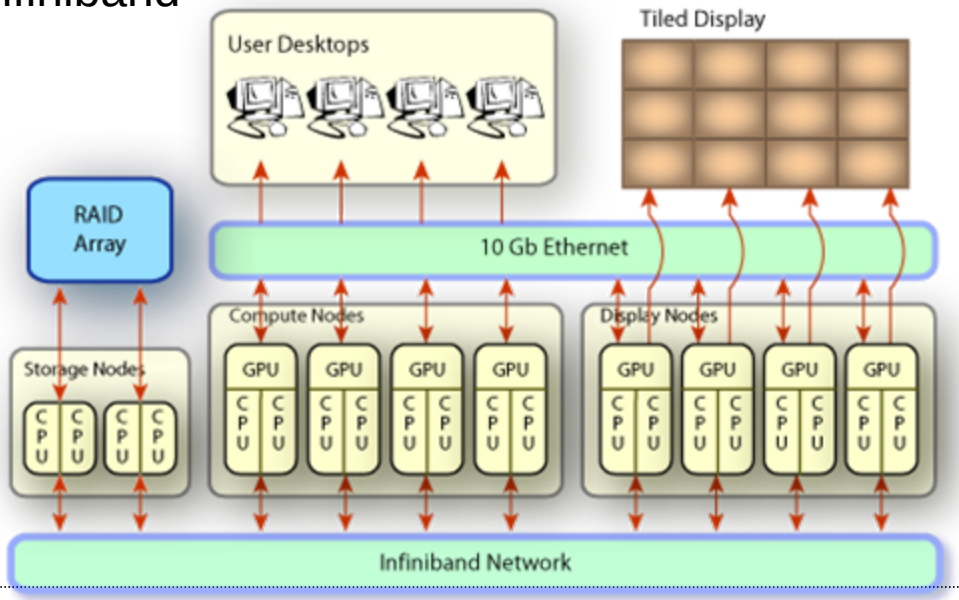
- Audioscapes, Image and Video Archives
- GIS (satellites to low-flying planes), Laser Scanners
- Medical Imaging (CT, MRI, fMRI, …)
- Molecular Imaging (NMR, Crystallography, Microarrays, …)

Generation:

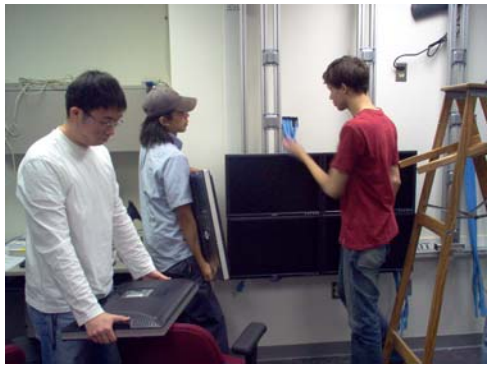
- Meteorology: Atmospheric simulation and prediction
- Biology: Molecular dynamics, protein docking
- Space Sciences: Solar wind turbulence, micro-gravity fluid mechs.
- High-Energy Physics: Multi-scale Plasma Dynamics

Maryland Chimera Project

- 15 Compute Nodes and 13 Render Nodes
- 4 Nodes for Scheduling and File Server
- 1 User node (keyboard, terminal)
- Each node has:
  - Dual 3GHz Intel Xeon CPUs
  - NVIDIA GeForce 7800 GTX GPU
  - 8 GB RAM
  - 100 GB Disk
- Parallel fileserver has 10 TB disk storage
- Network interconnect: 10 Gbps Topspin Infiniband

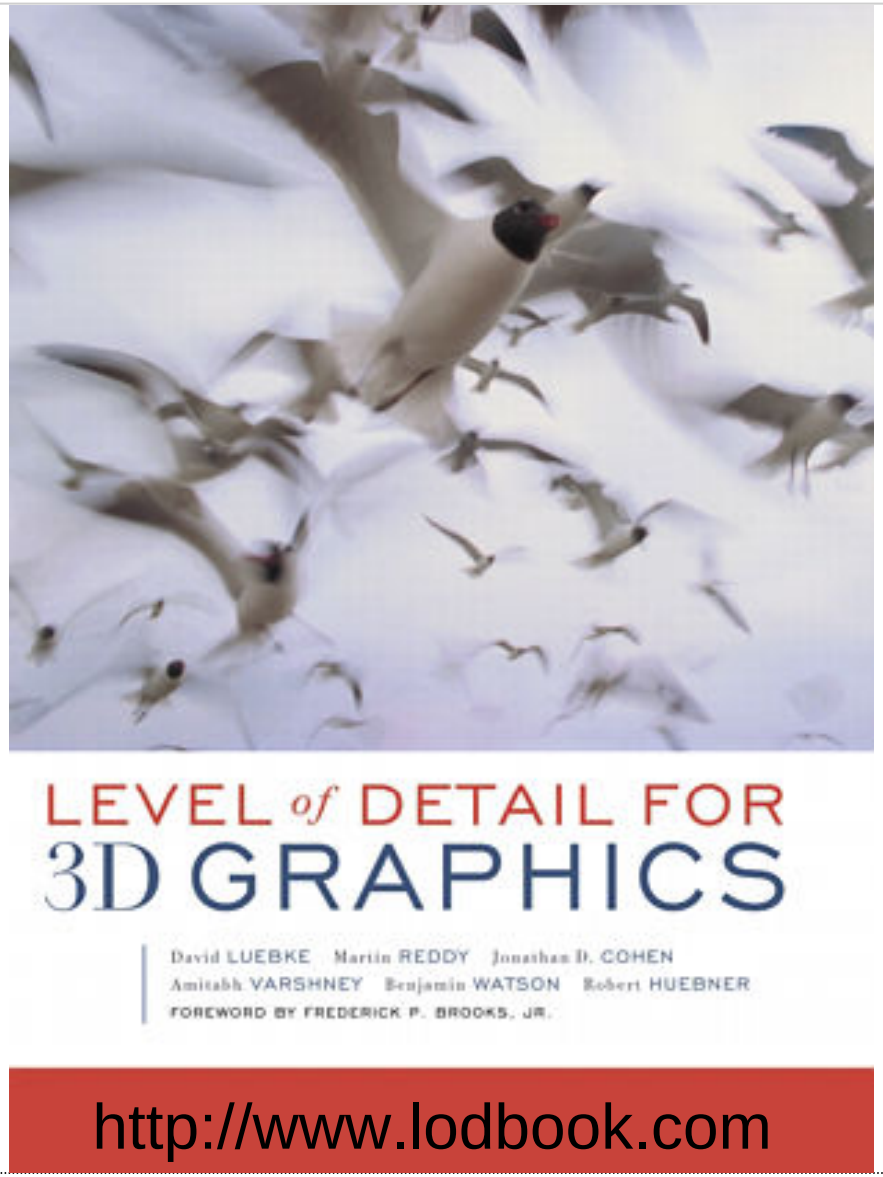


Chimera Project: Tiled Display



Total resolution: 50 mega pixels
(5 x 5 array of 1920 x 1200 Dell 24” LCD screens)
Ultrasonic air-mouse interface

Multiresolution Representations



http://www.lodbook.com

The Last Inch Problem

- Data complexity is rising
- Computing capabilities are increasing
- Human perceptual and cognitive machinery remains largely unchanged

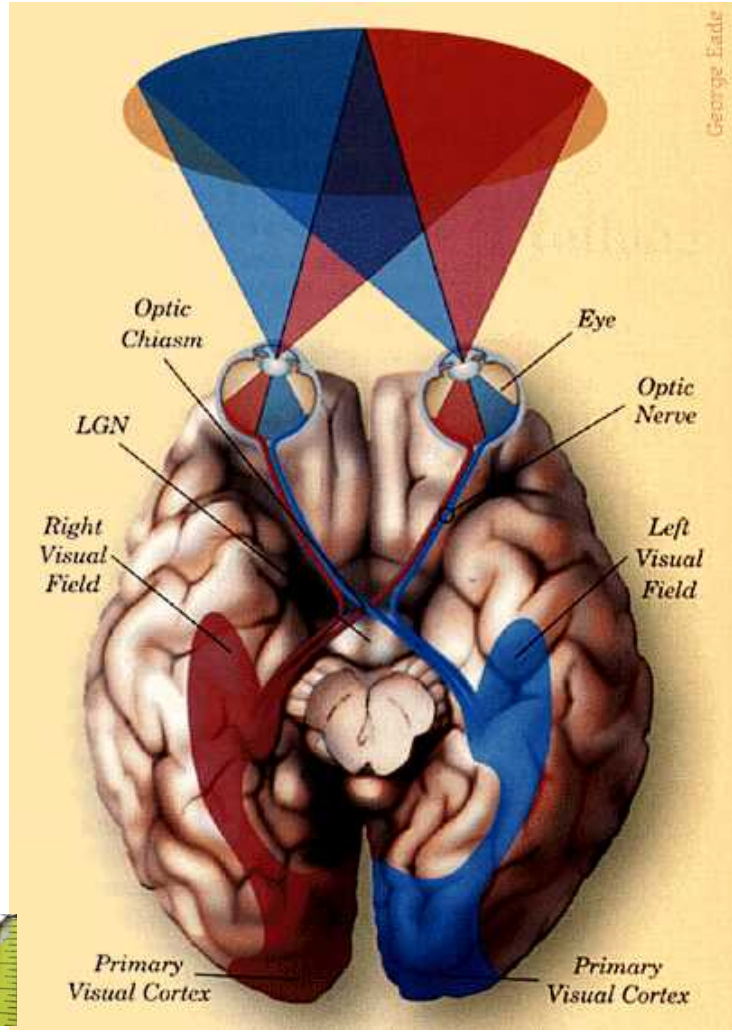
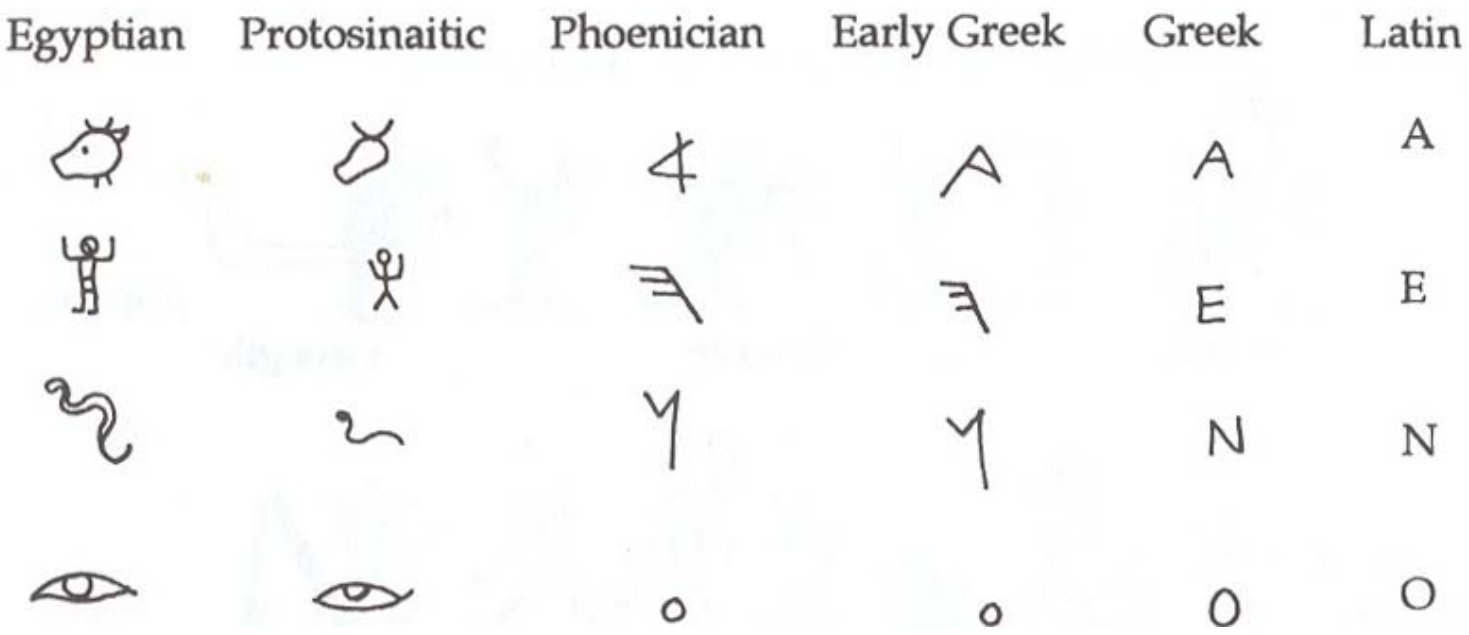


Image courtesy of Howard Hughes Medical Institute

Abstraction

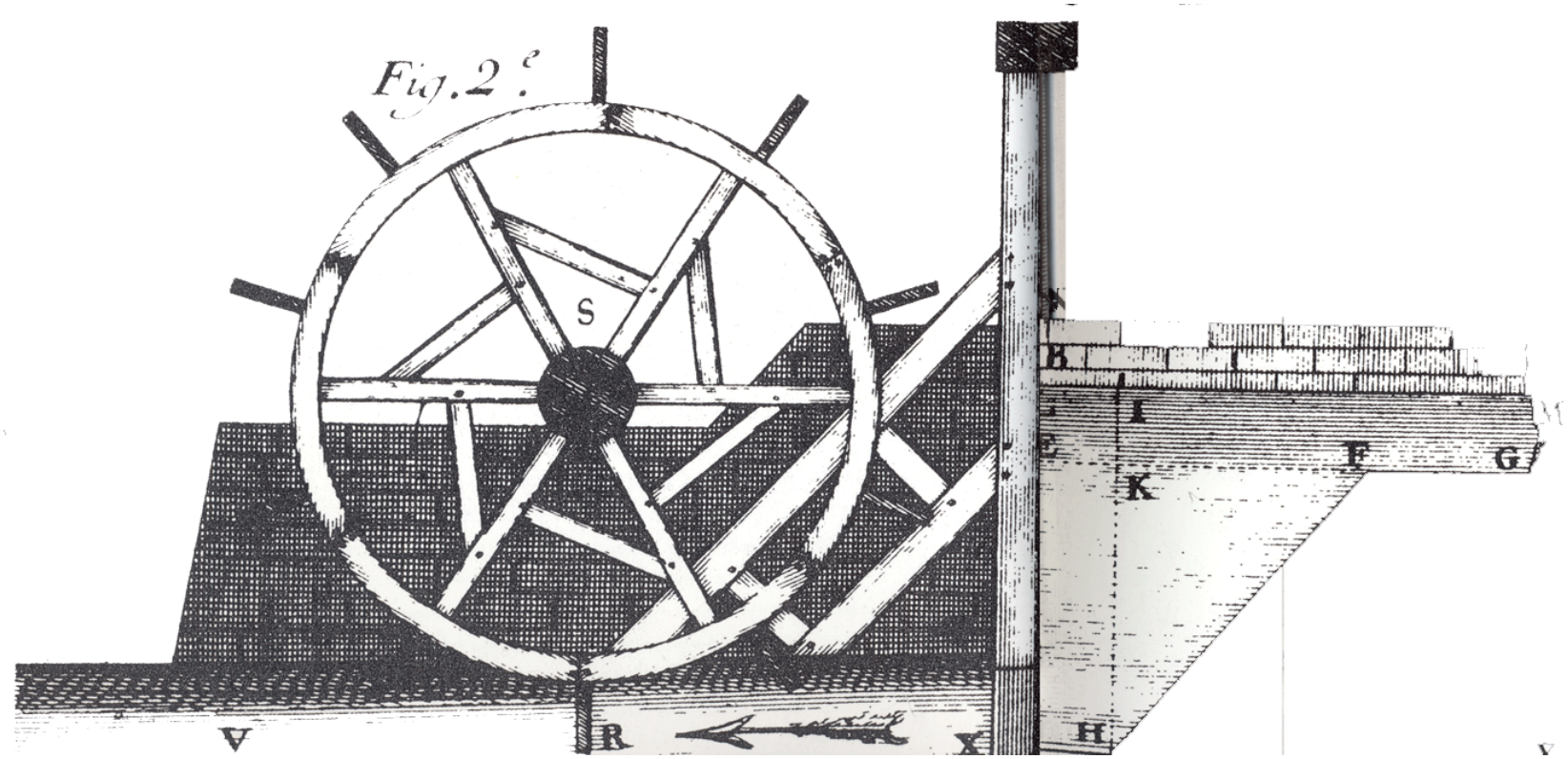
Can we decouple the visual representation from the physical representation ?



Yes, but how about just visual depiction …

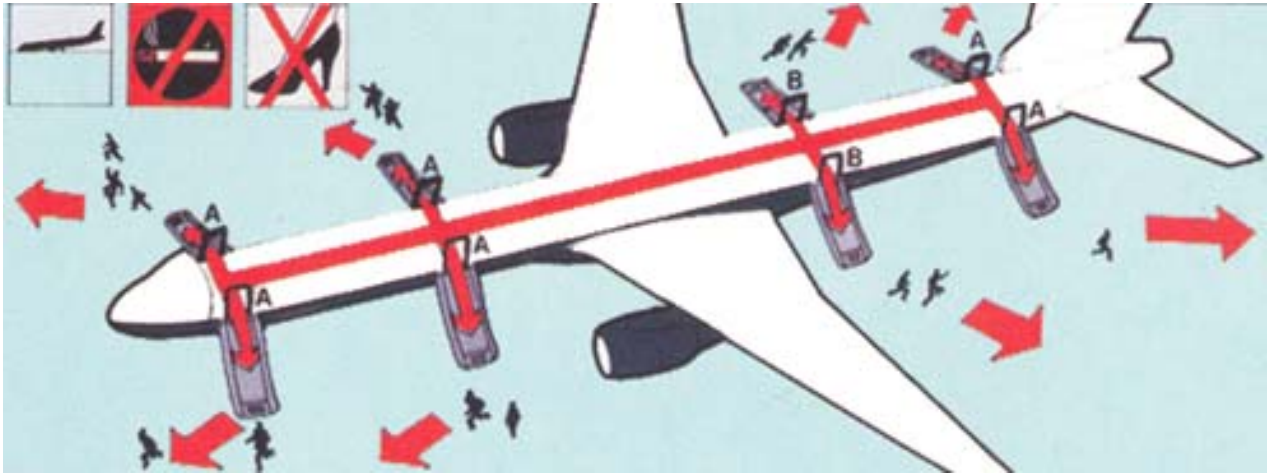
from Visual Intelligence by Ann Marie Barry

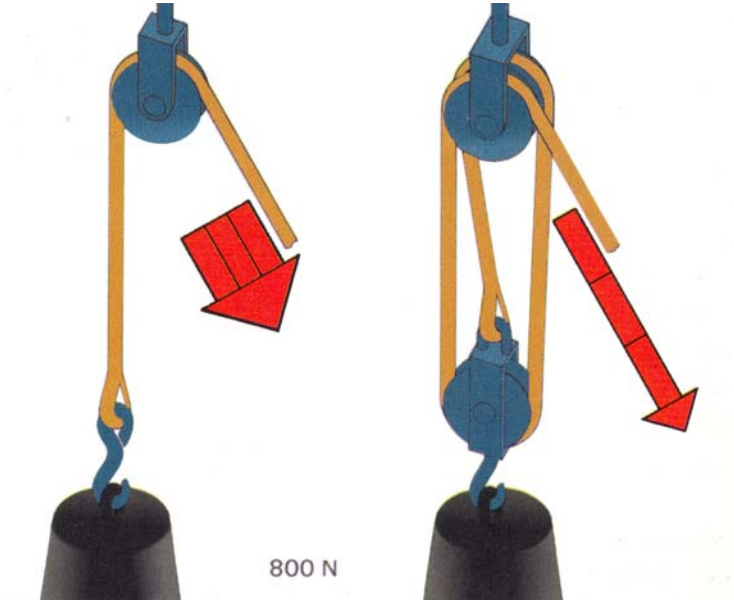
Arrows in Visual Depiction

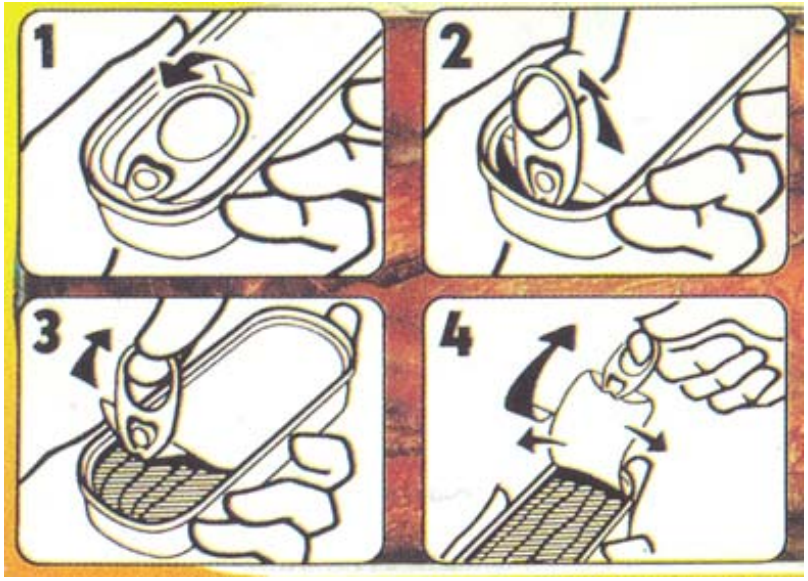


by Bernard Forest de Belidor in Architecture hydraulique, 1737

Arrows in Visual Depiction





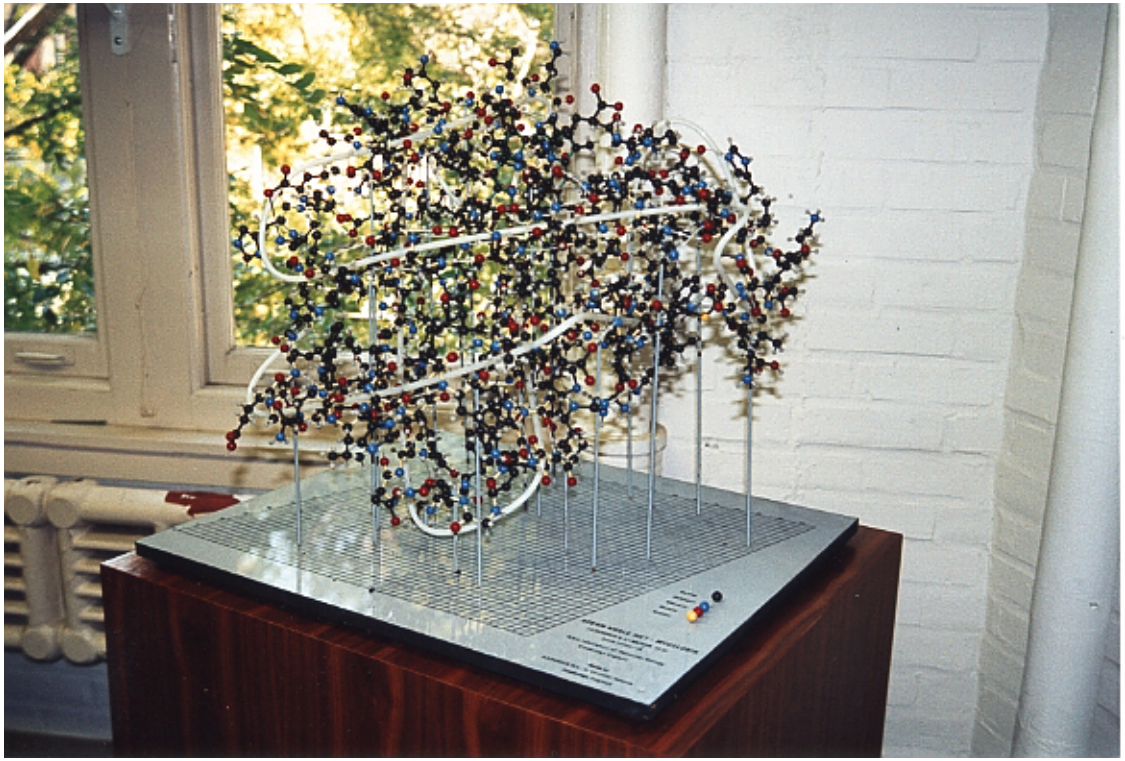


from Open Here by Mijksenaar and Westendorp

Visual Abstractions

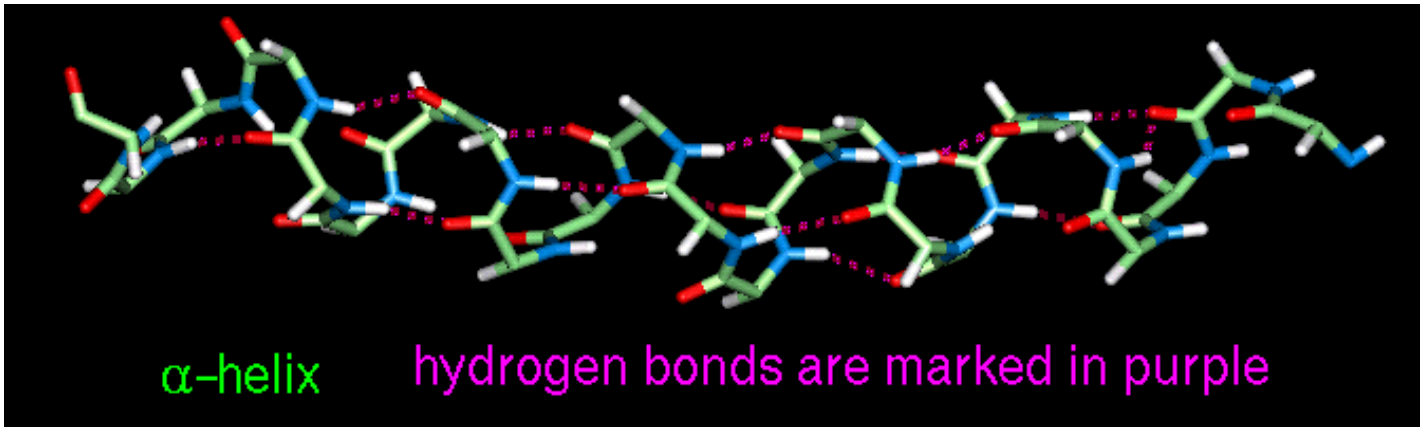
- Arrows are a convenient visual abstraction of motion

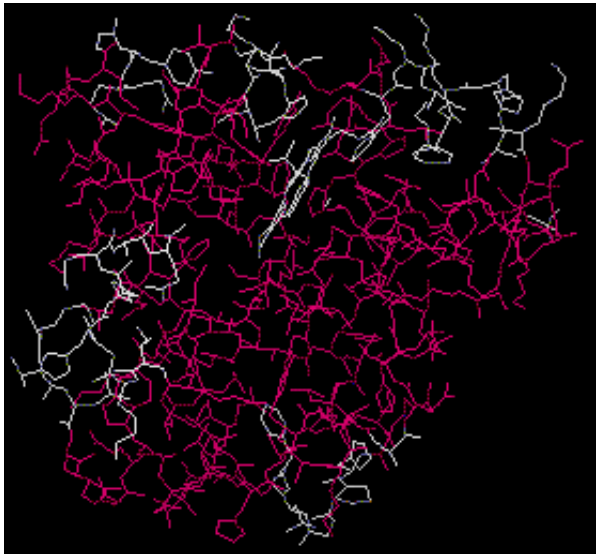
- How about visual abstractions of geometry?

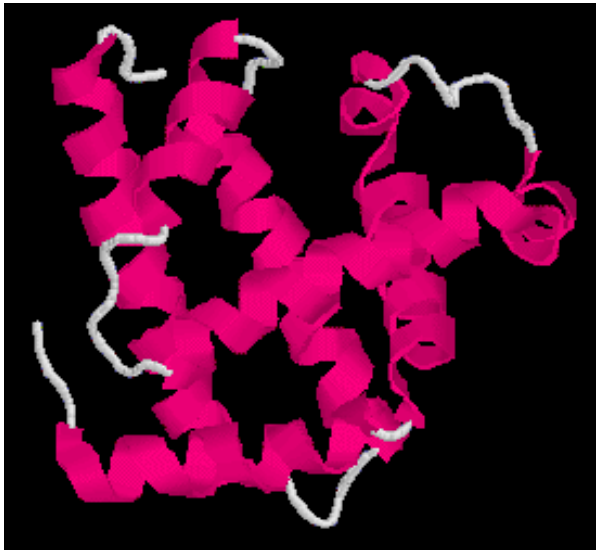


Model of Myoglobin made by A. A. Barker (Cambridge, UK) in 1966 for £210. Currently owned by Dr. Britton Chance

Visual Abstractions of Proteins







Myoglobin Representations

Abstraction first proposed by Jane Richardson in 1981 (Adv. In Prot. Chem.)

Summary (thus far ...)

- Decoupling physical realism from visual representation can be very powerful
- Identify what is important for the task (Saliency)
- Emphasize salient attributes

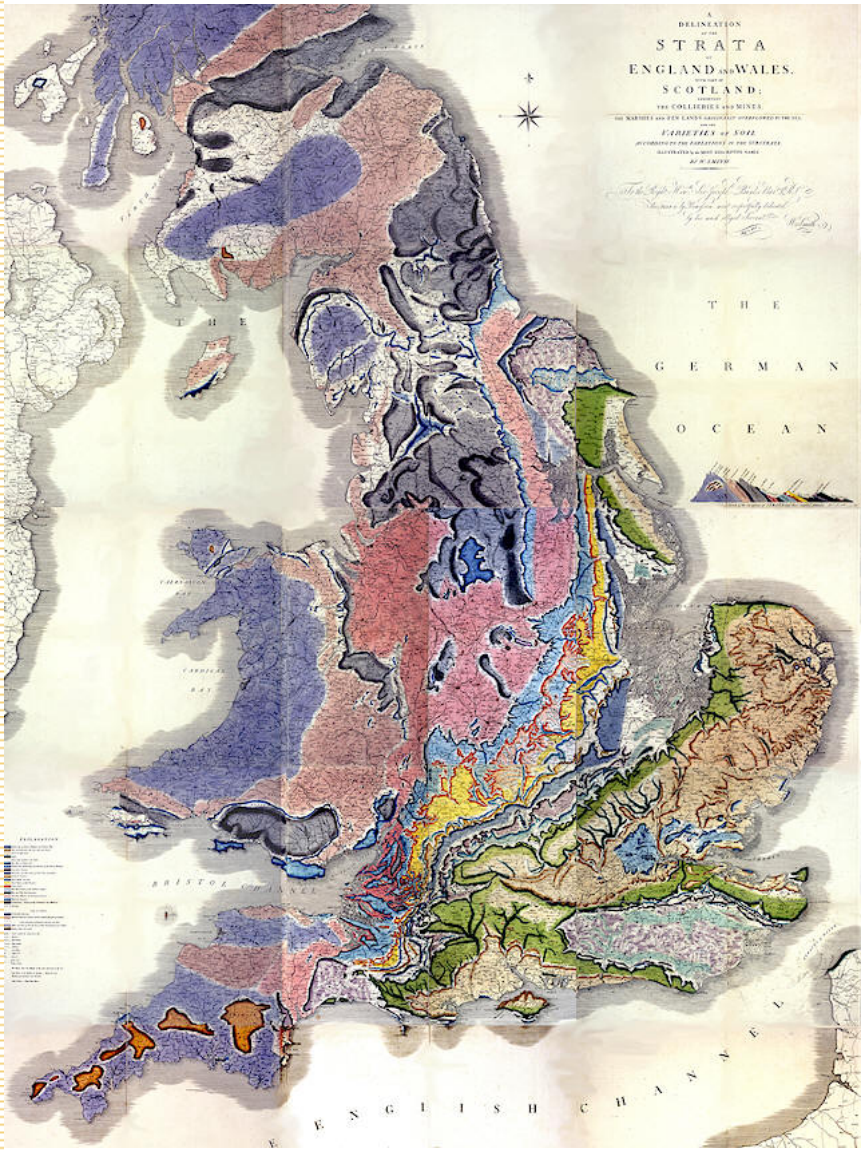
Salient Visualization: Geology

- Observed stratification of rocks during his work on coal mines and later canals
- The *order* of rocks were the same
- The *depths* at which they occurred differed
- Hypothesized a 3D structure of layers at various slopes beneath the Earth's surface
- Used measurements along canals, mine shafts, and extrapolated…

William Smith (1769 – 1839)

from *The Map That Changed the World* by *Simon Winchester*

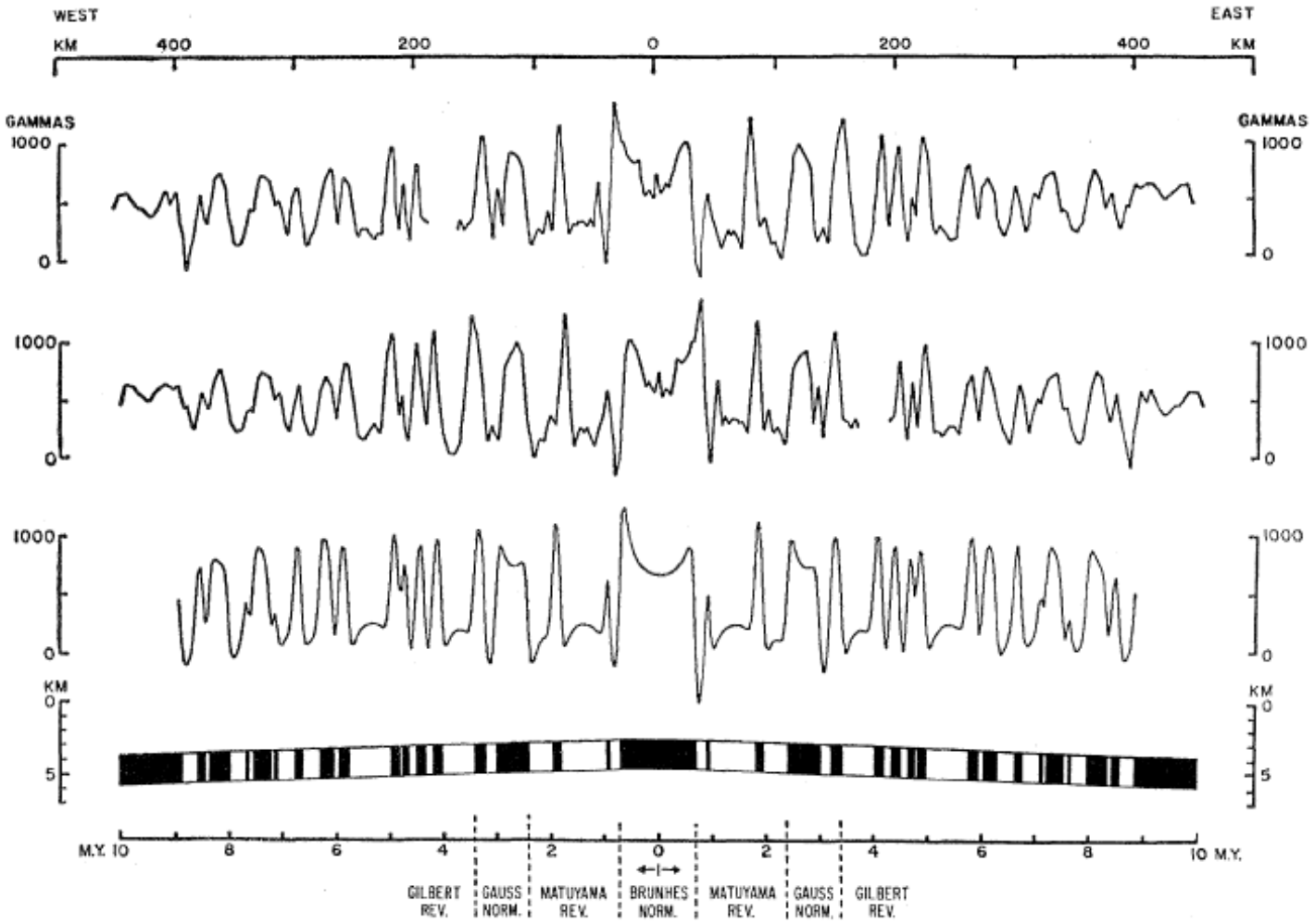
Salient Visualization: Geology



- The *first* systematic spatial study of various rock strata
- Used fossil types in various layers of rocks to fine-tune
- Created the *first* geological map in 1815
- Visually persuaded the world of the innate structure of the Earth; immensely influential in:
  - Geology
  - Natural History and Biology
  - Mining coal, oil, iron, diamond, platinum, silver, …

from *The Map That Changed the World* by *Simon Winchester*

Salient Visualization: GeoPhysics

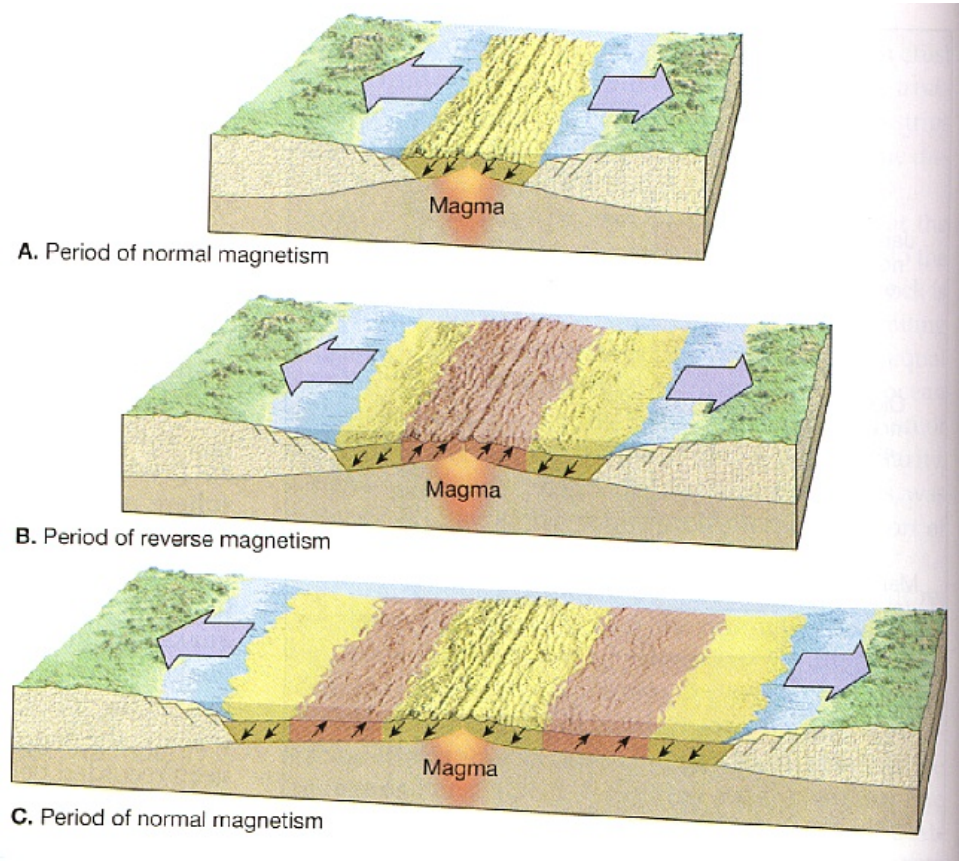


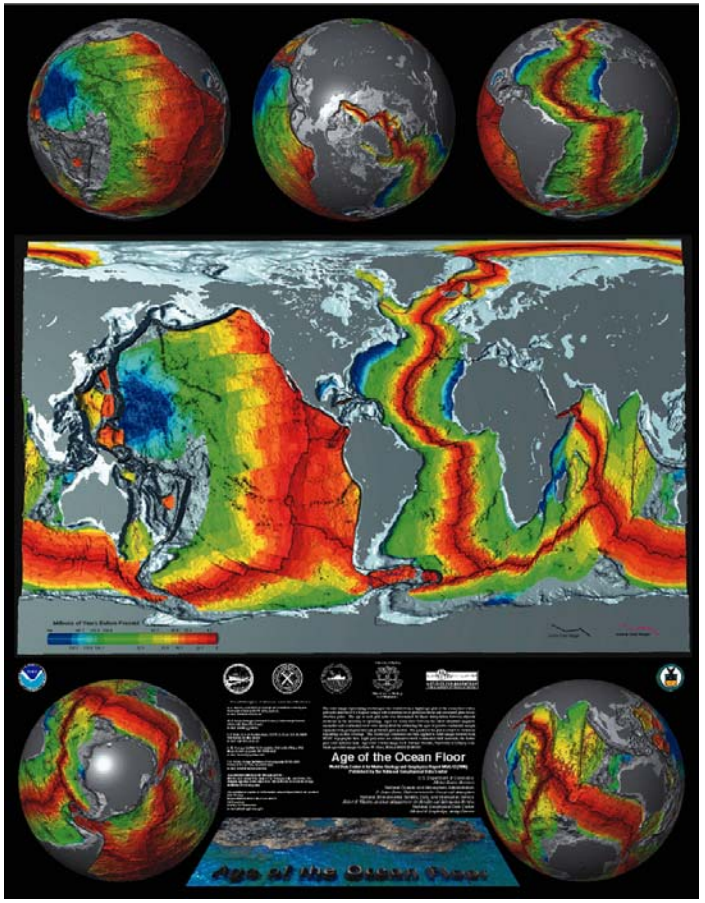
Magnetic Profile and Bathymetry data from USS Eltanin, track 19

From Pitman and Heirtzler, Science, Dec 1966

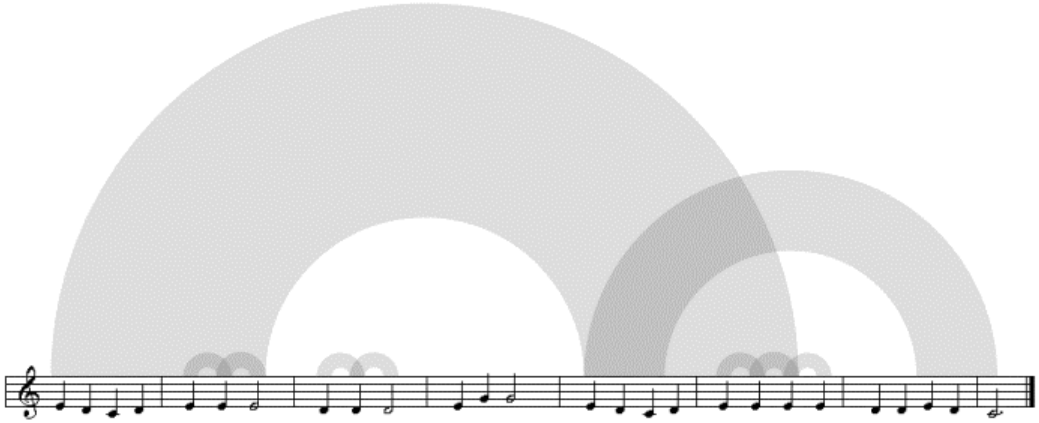
Salient Visualization: GeoPhysics

- The *first* visual proof of symmetry of magnetic anomalies
- Visually persuasive evidence leading to the acceptance of the theory of sea-floor spreading

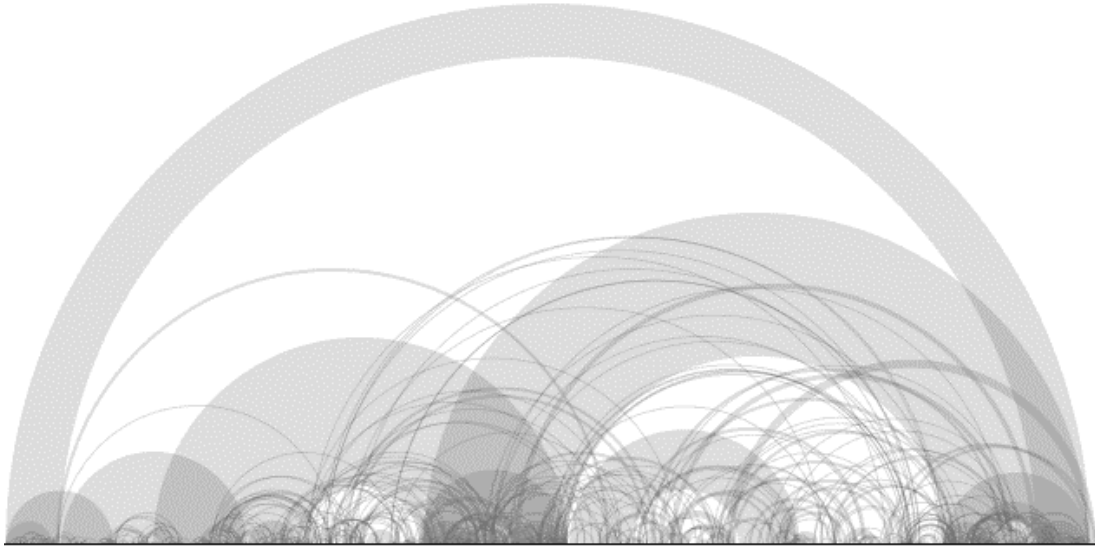




Salient Visualization: Music



Mary had a Little Lamb



Beethoven's Für Elise

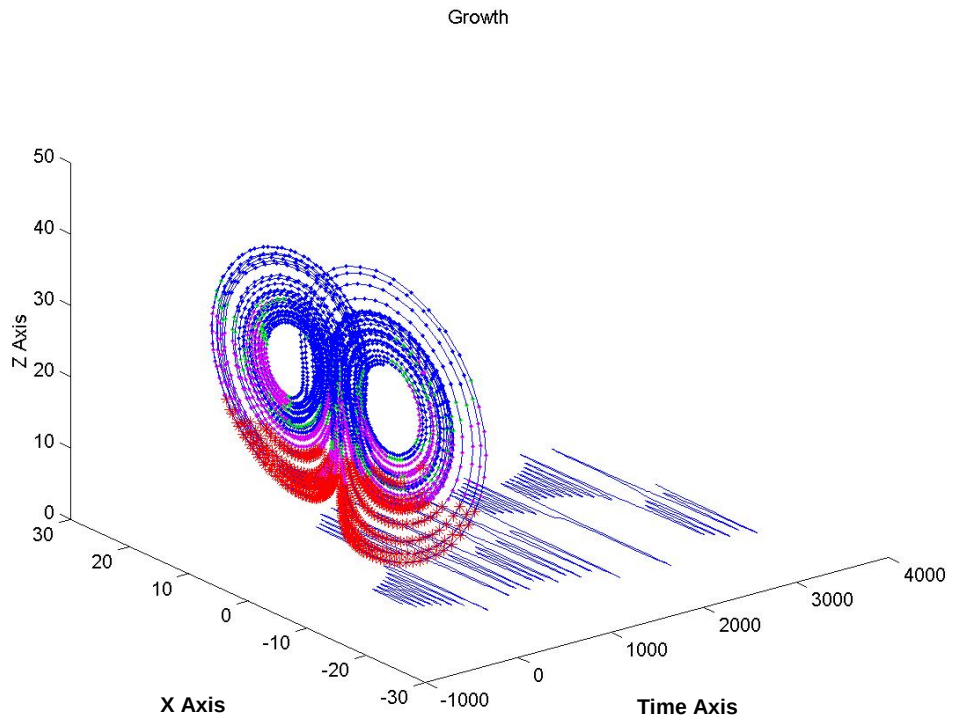
Arc Diagrams by *Martin Wattenberg, IEEE InfoVis 2002*

Lorenz (1963) 3-variable model

$$\frac{dx}{dt} = \sigma(y - x)$$

$$\frac{dy}{dt} = rx - y - xz$$

$$\frac{dz}{dt} = xy - bz$$



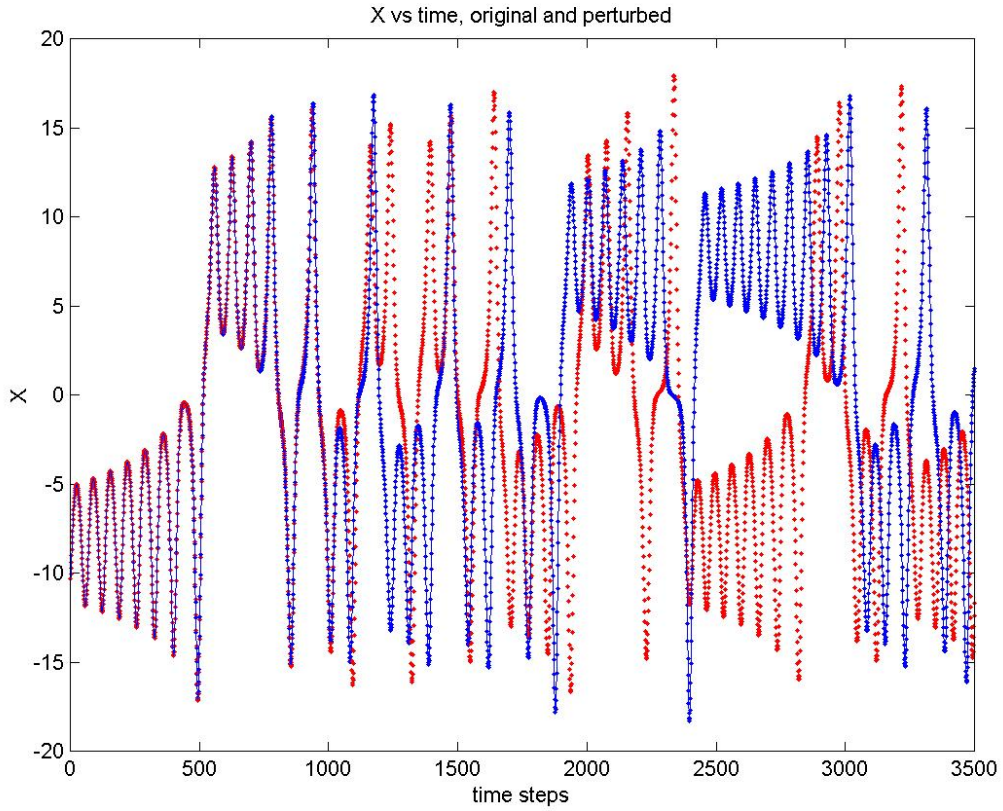
Has two regimes and the transition between them is *chaotic*

Definition of Chaos

When the Present determines the Future, **but**

the Approximate Present does not

Approximately determine the Future

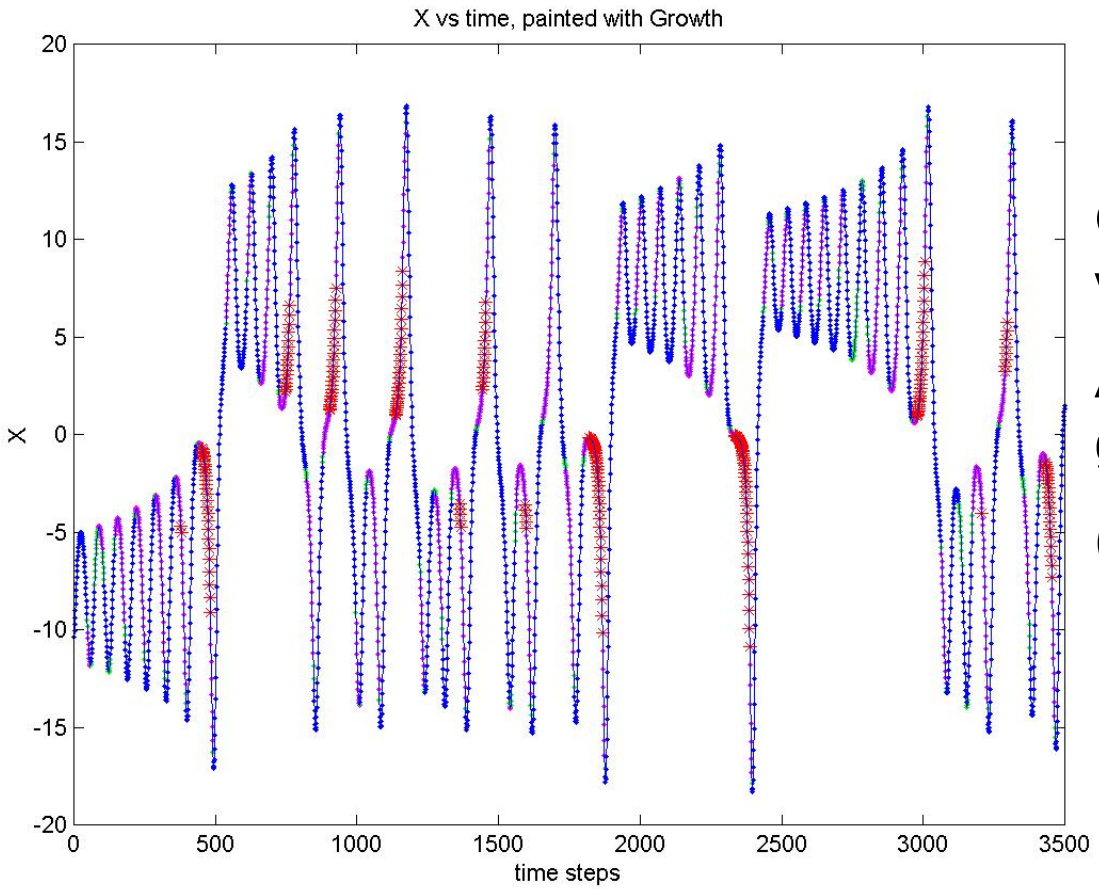


Lorenz, March 2006

89 years old

Salient Visualization: Chaos

Kalnay asked the interns to mark x(t) with the bred vector growth and was surprised to see the dramatic results:



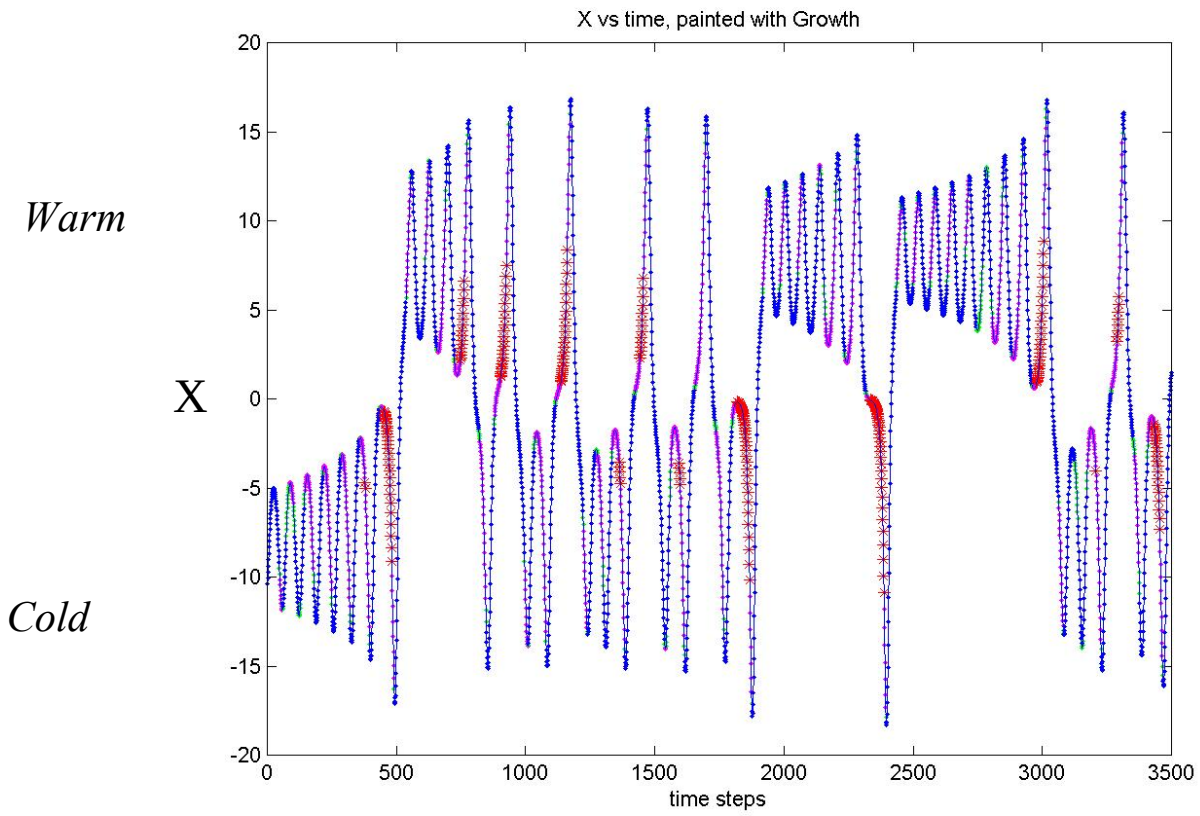
Growth rate of bred vectors:

A * indicates fast growth

(>1.8 in 8 steps)

Eugenia Kalnay

Salient Visualization: Chaos



Growth rate of bred vectors:

A * indicates fast growth

(>1.8 in 8 steps)

Regime change: The presence of red stars (fast BV growth) indicates that the next orbit will be the last one in the present regime.

Regime duration: One or two red stars, next regime will be short. Several red stars: the next regime will be long lasting.

General Observations

- Common amongst examples
  - Carefully hand-crafted
  - Took immense effort
  - One of a kind

- General principles:
  - Results convey important elements in a clean and visually consistent way
  - They emphasize *salient features* and suppress others
  - They are parsimonious visualizations and they make the few resources work extra hard (space, color, …)

Visual Computing

- The process of transforming data to images involves
  - Dimension explosion – add normals, reflectance, camera, lighting, transfer functions, …
  - Dimension reduction – incorporate everything to give us colors and their locations
- How is data salience propagated through such a pipeline?
  - Are we certain it survives?
- Every communication has a message
  - And every point and every voxel a default importance
- How can we preserve data salience in rendered images?

Visual Computing

- Visual attention
  - How does one draw visual attention?
- Saliency
  - How does one compute saliency?

Directing Visual Attention by Light

Joseph's Bloody Coat Brought to Jacob, Velasquez 1630

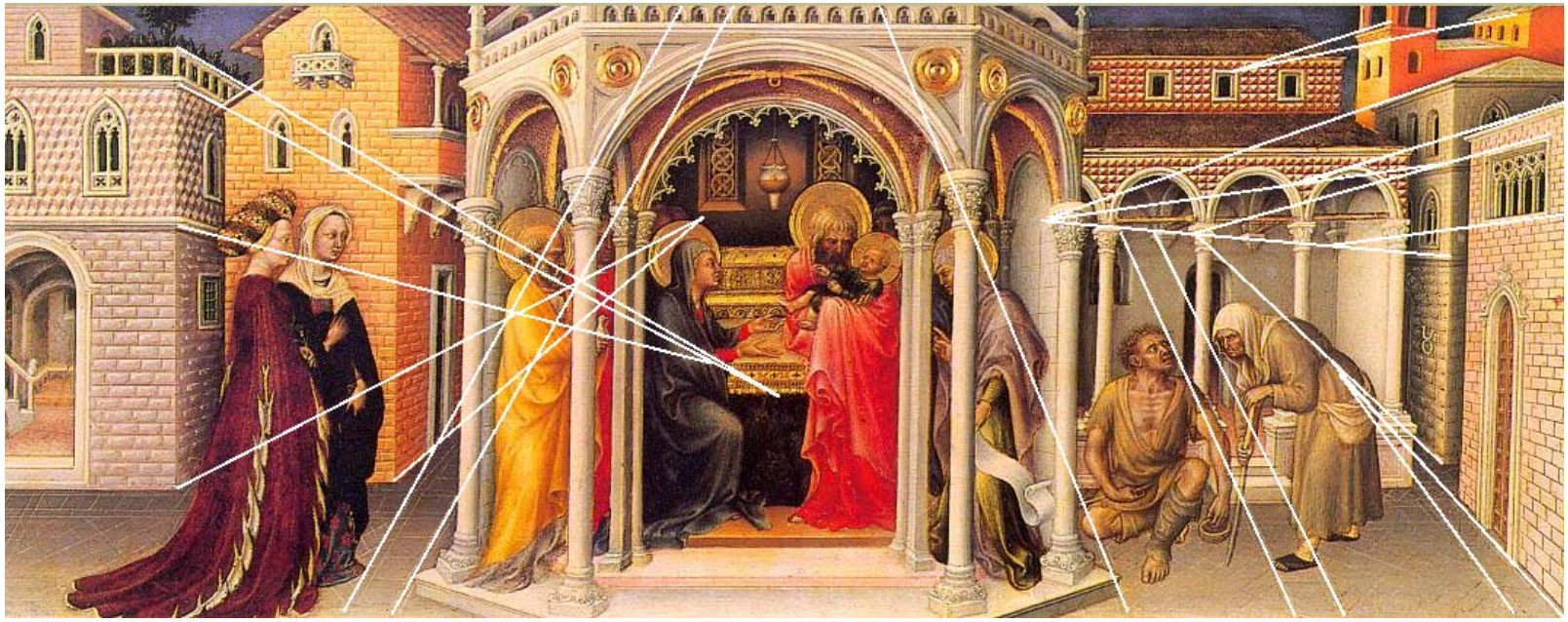
Visual Continuity & Consistency

- Shots often composited from multiple takes
- Lighting is painstakingly made consistent
- Consistent lighting considered important for visual continuity and storytelling

Jurassic Park, © Universal Studios

Is Consistent Lighting Necessary?

- Nature has one dominant light source
- Evolution might have endowed us with an ability to discern inconsistency in illumination
- Just as it has inconsistency in perspective



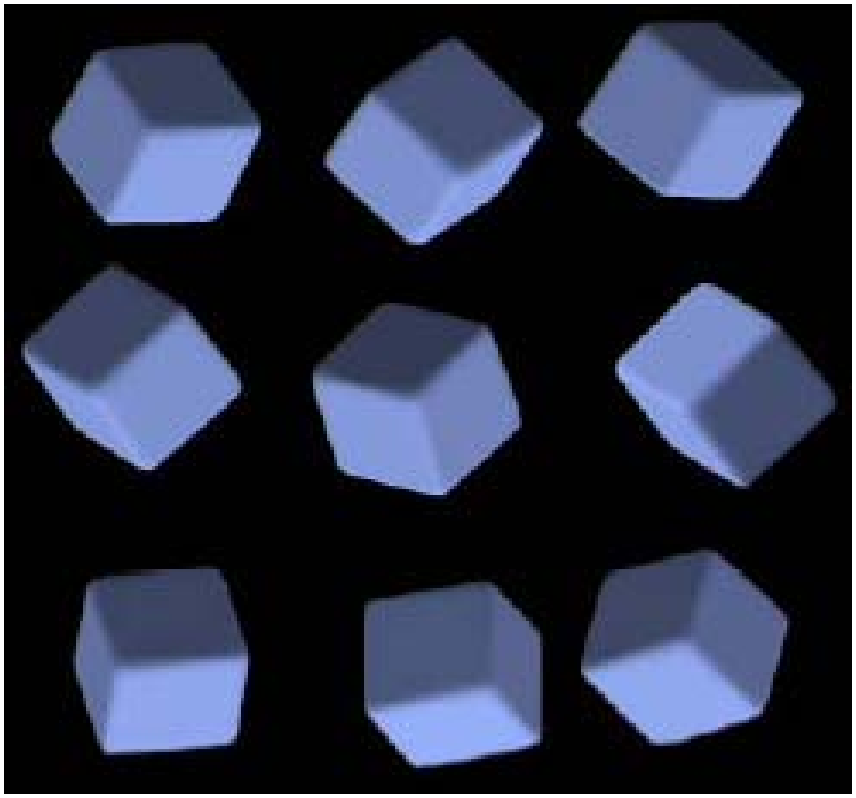
The Presentation in the Temple by Gentile da Fabriano (1423)

Analysis of Perspective by Chris Tyler, Smith-Kettlewell Institute

Illumination Inconsistencies

Recent research suggests that illumination consistency is *not* resolved at the low-level human vision

Find the cube lit inconsistently with respect to others:

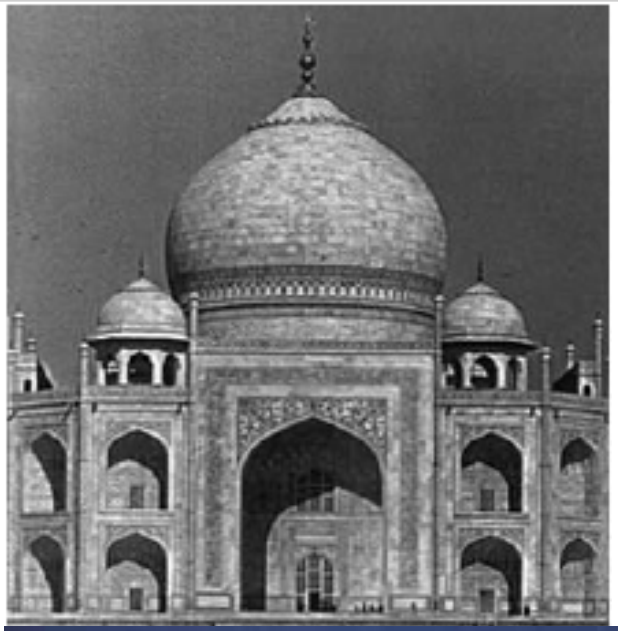


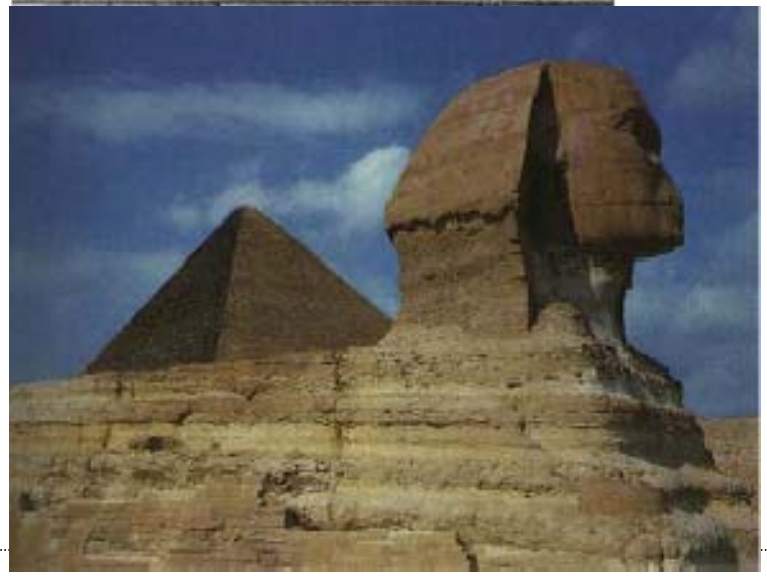
On average, users take 8 seconds to answer and are then wrong 30% of the time

Illumination inconsistencies are not perceptually salient

Ostrovsky, Sinha, Cavanagh, *Perception 2006*

Illumination Inconsistencies





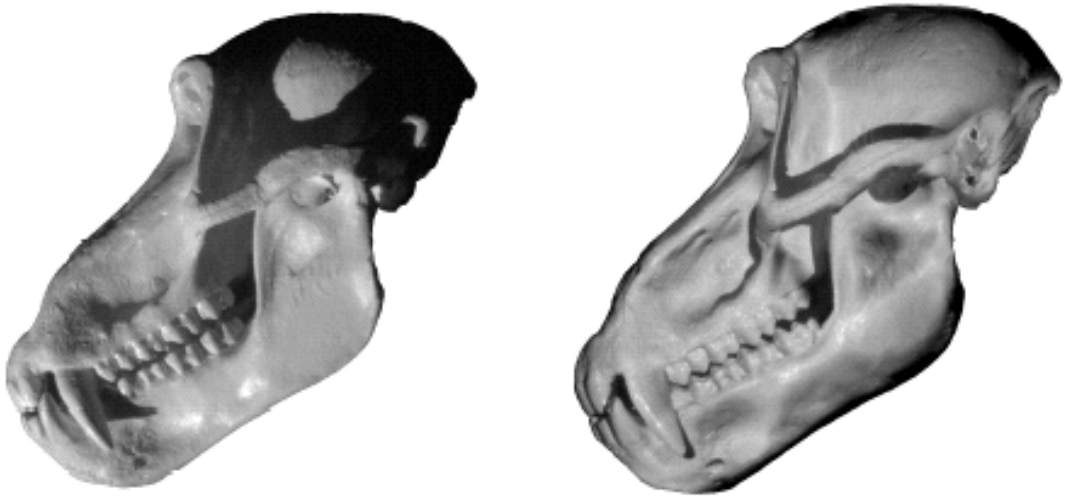
Ostrovsky, Sinha, Cavanagh, *Perception 2006*

Discrepant Lighting in Art

The Music Lesson by Jan Vermeer

Discrepant Lighting

- Scientific visualization need not strive for photorealism
- Discrepant lighting can yield compelling results

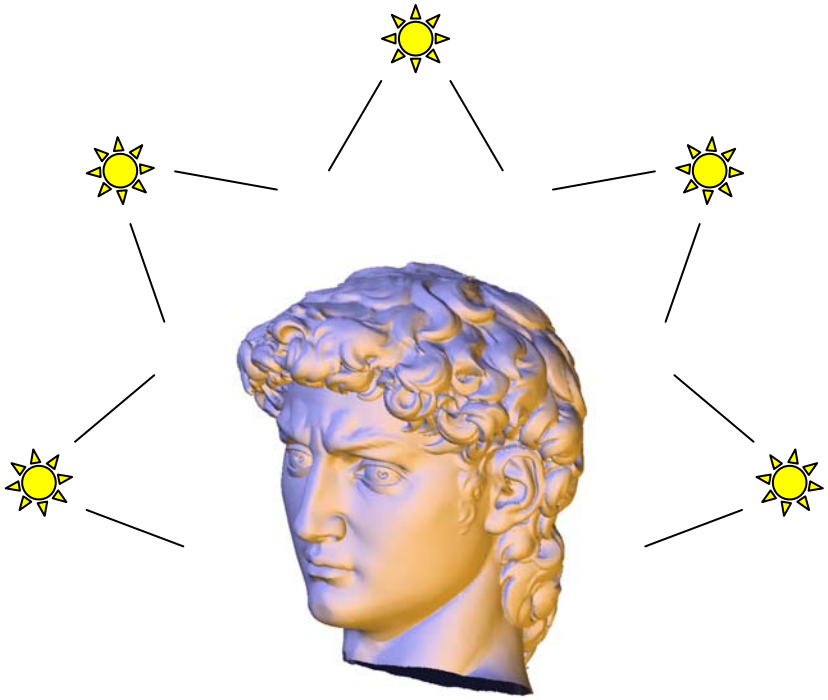


Consistent Discrepant

Akers, Losasso, Klingner, Agrawala, Rick, Hanrahan, *Visualization 2003*

Light Collages: Basic Idea

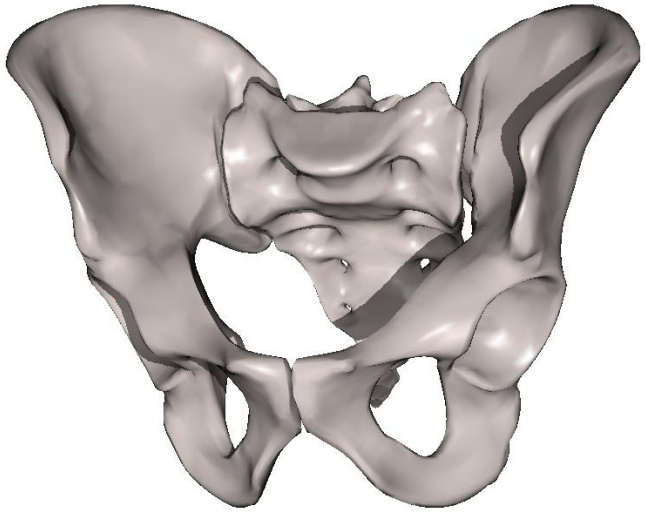
Allow local lighting parameters to be defined independently at local regions

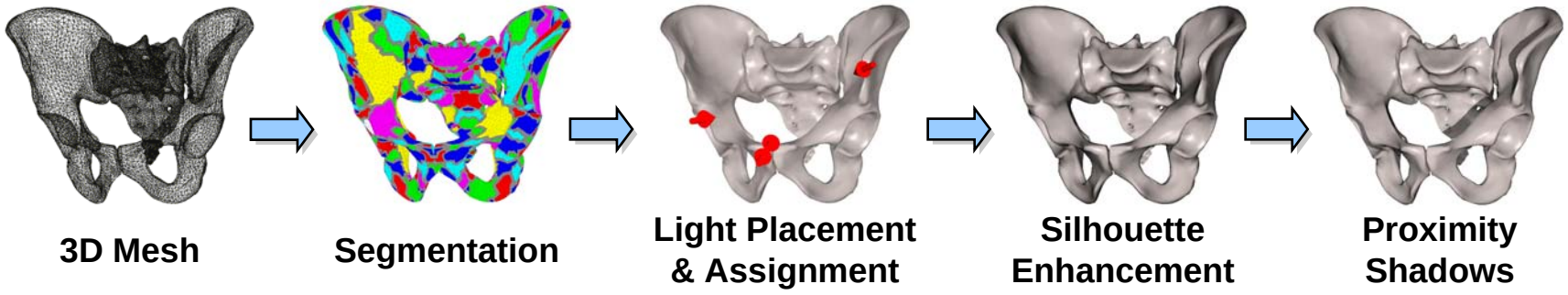


Lee, Hao, Varshney, Visualization 2004, TVCG 2005

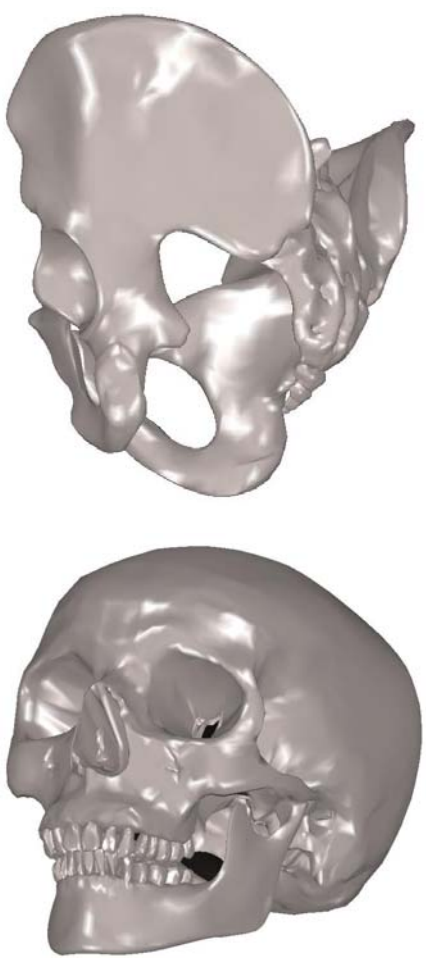
Light Collages Overview

- Segmentation
- Light Placement and Assignment to patches
- Silhouette Enhancement
- Proximity Shadows

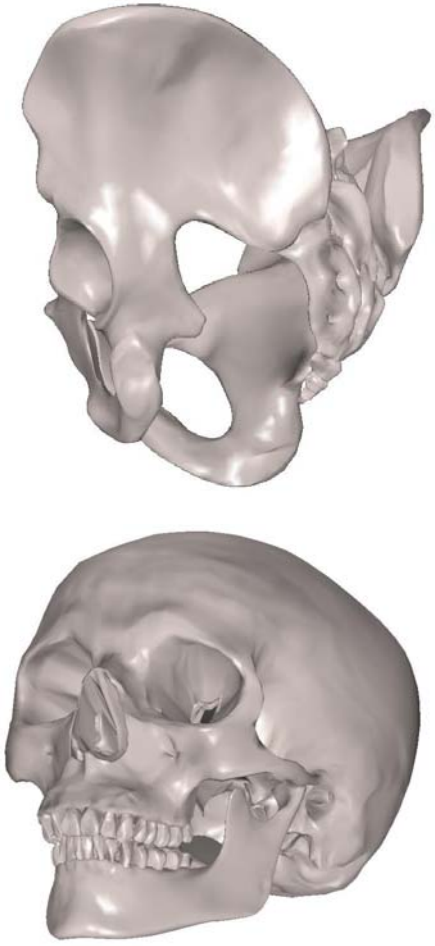




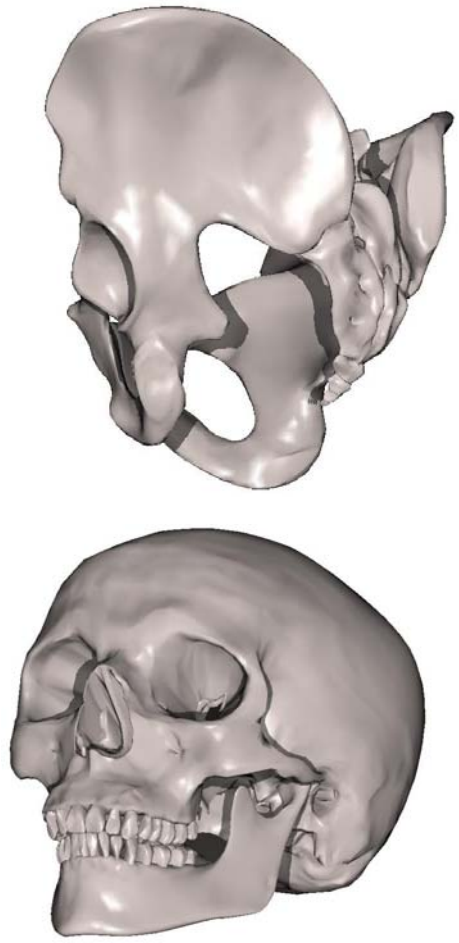
Results – Pelvis & Skull



(a) Uniform 4 lights

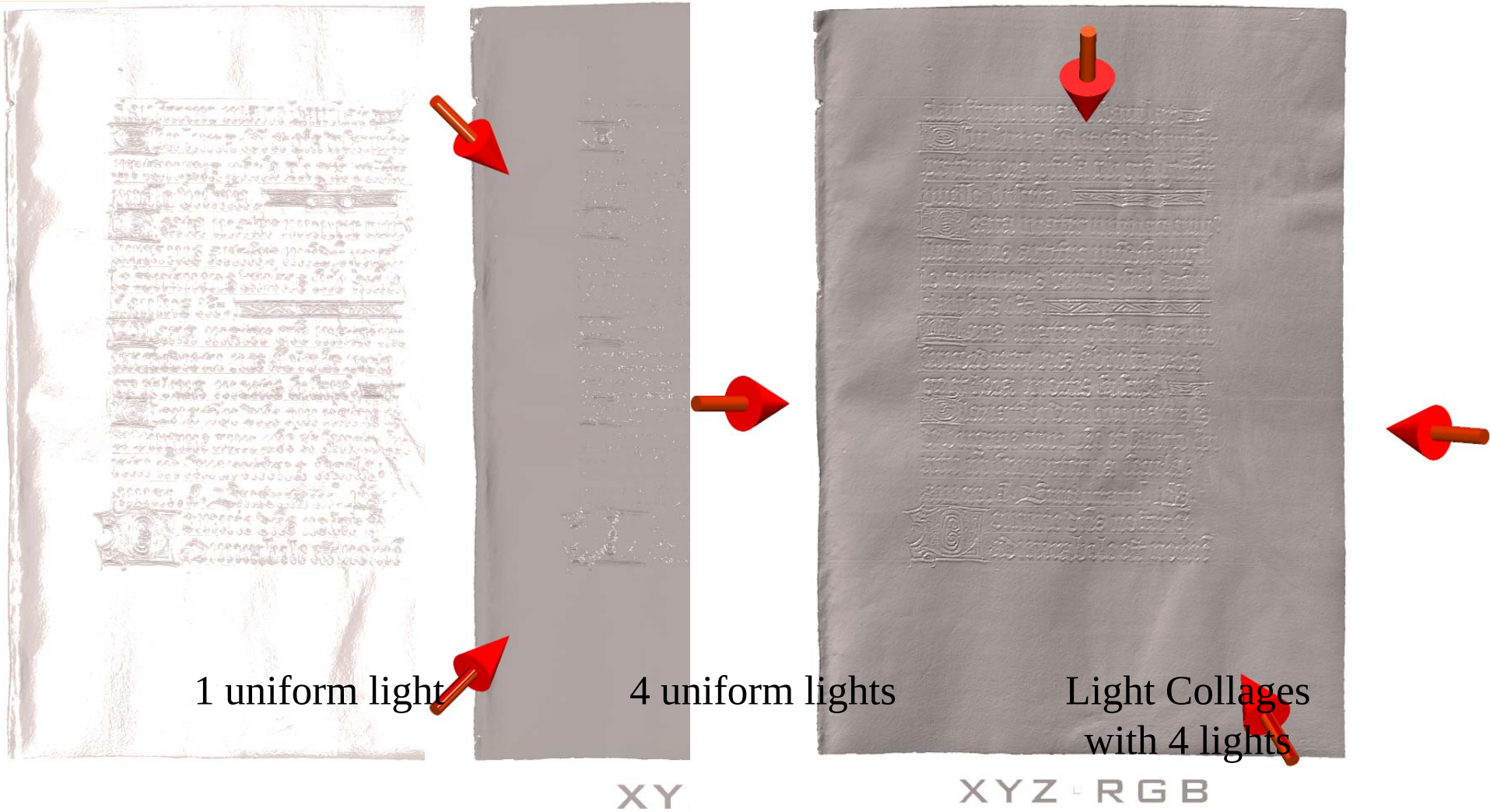


(b) Light Collages: with 4 lights



(c) Light Collages: Silhouettes+ Shadows

Results - Manuscript



Manuscript courtesy of Paul Debevec, USC and XYZ RGB Inc.

Visual Attention

A wealth of information creates a poverty of attention and a need to allocate it efficiently.

Herbert Simon

A way of seeing is also a way of not seeing – a focus on object A involves a neglect of object B

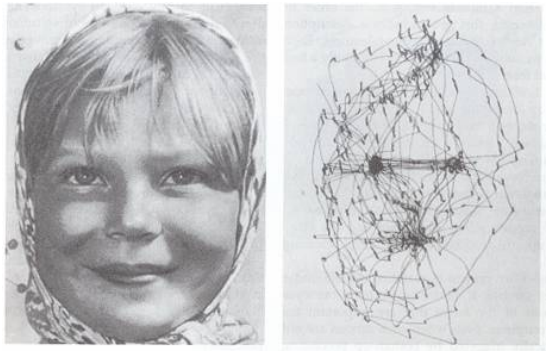
Kenneth Burke

Visual Attention

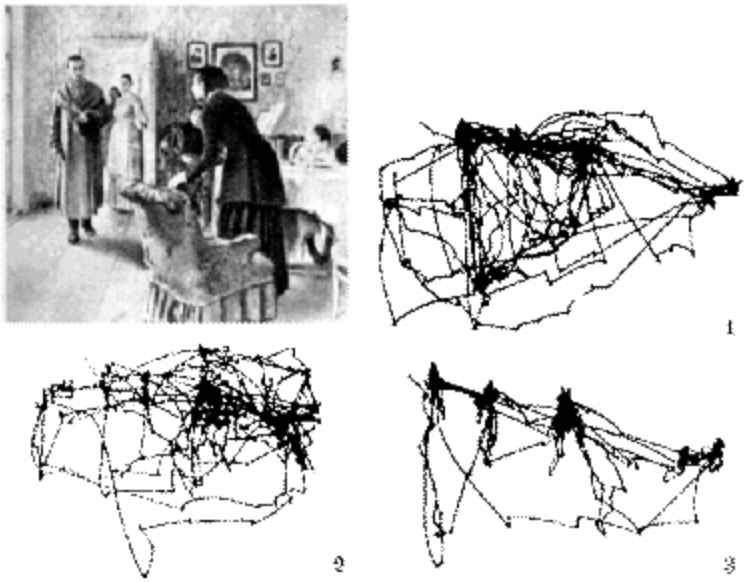
- Where we look has significant implications for:
  - what we perceive
  - how we interpret
  - how we act
- Visual attention is the primary filter by which we can cope with our immense sensory bandwidth
  - Retinal information is too vast and most of it has no survival value
- Eye-tracking can quantify overt visual attention

What Controls Visual Attention

Bottom-up Image Properties (task independent)



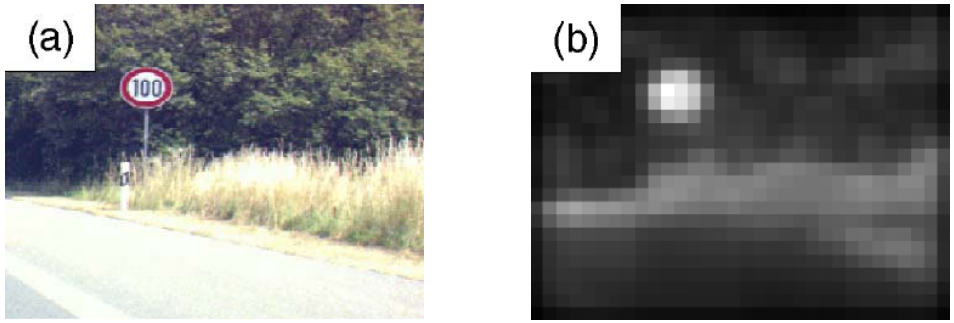
Top-down Semantics and Task-driven Properties



Yarbus 1967

Related Work

- Image saliency maps
  - Tsotsos *et al.* 95, Milanese *et al.* 94, Itti *et al*. 98, Rosenholtz 99



Itti *et al.* PAMI 98

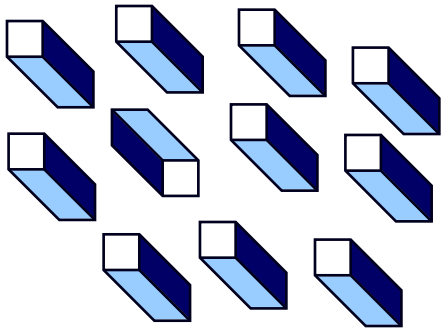
- Applications: compression and cropping
  - Privitera and Stark 99, Chen *et al*. 03, Suh *et al*. 03

Without cropping

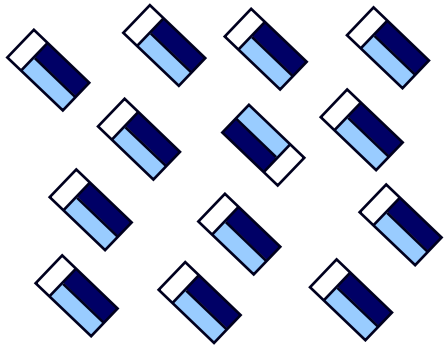
Saliency-based cropping

Suh *et al.* UIST 03

Saliency has a 3D Component



3D features
pop out quickly



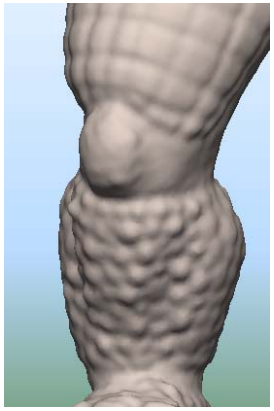
2D features
not pre-attentive

Based on Enns and Rensink 90

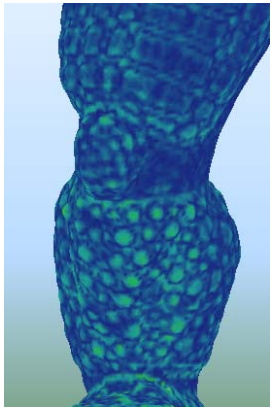
Distinctive 3D structure pops out pre-attentively

Mesh Saliency

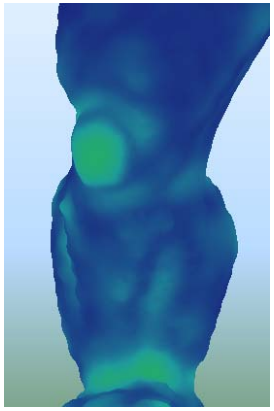
Saliency should find regions different from surrounding context



Armadillo Leg

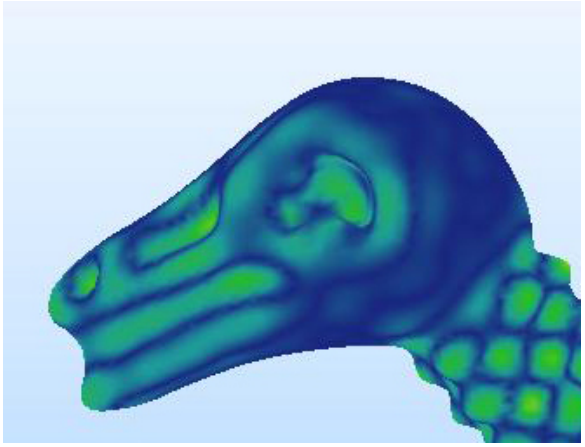


Curvature

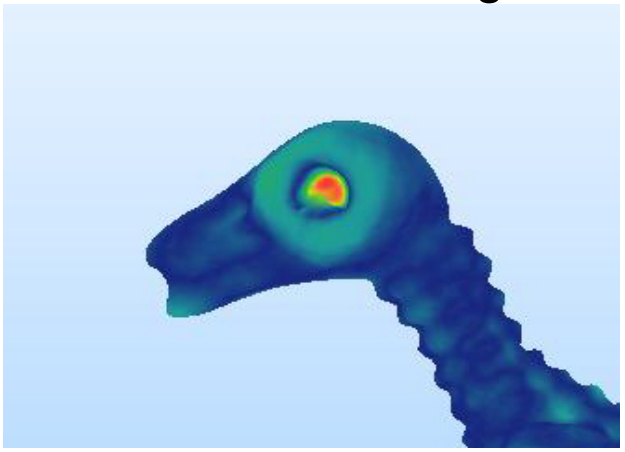


Saliency

Saliency should capture interesting features at all meaningful scales

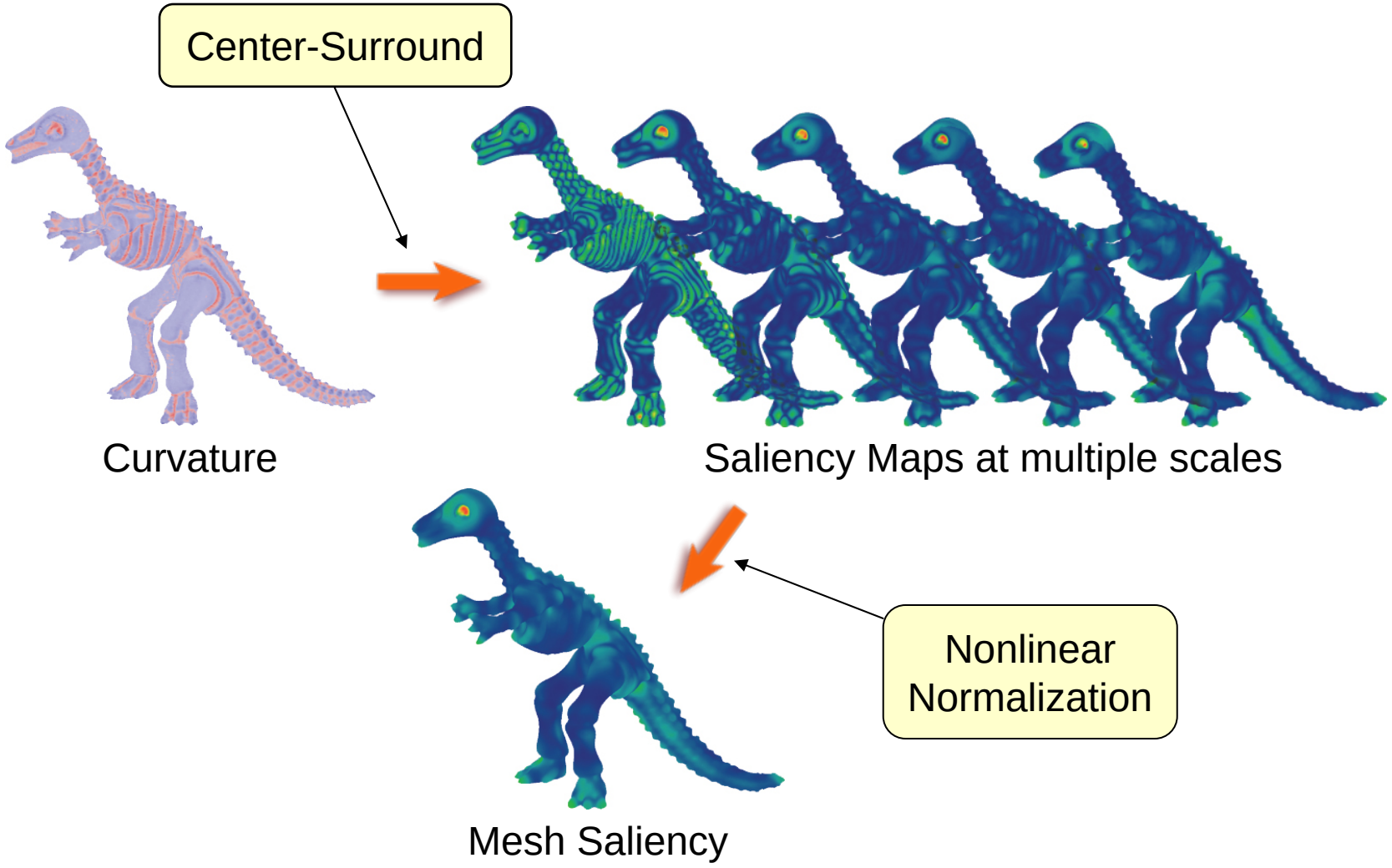


Saliency at a large object scale



Saliency at a small object scale

Saliency Computation Overview



Lee, Varshney, Jacobs, SIGGRAPH 2005

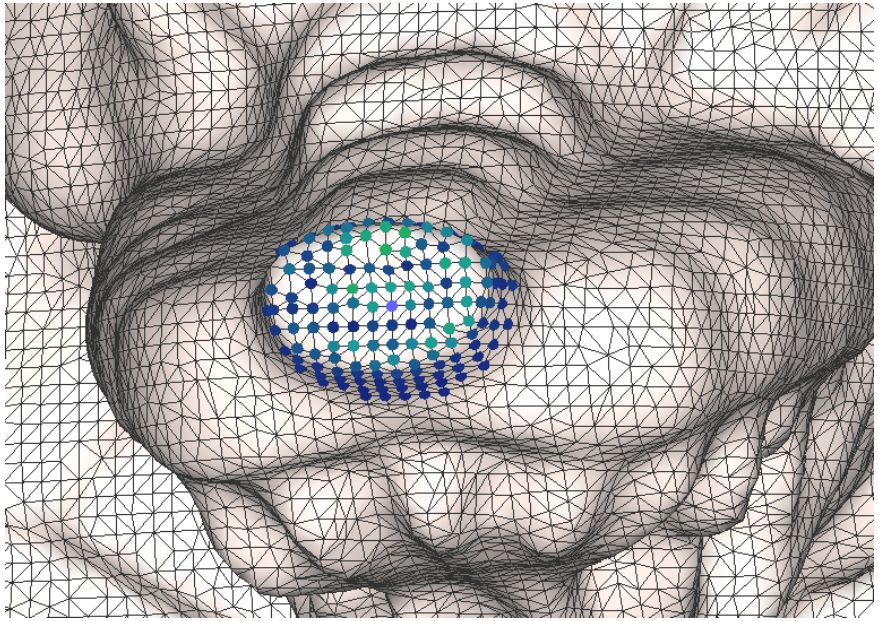
Center-Surround Operator

Gaussian-weighted average is:

$$G(\mathrm{C}(v),\sigma) = \frac{\sum_{x \in N(v,2\sigma)} \mathrm{C}(x)\, exp[-\|x-v\|^2/(2\sigma^2)]}{\sum_{x \in N(v,2\sigma)} exp[-\|x-v\|^2/(2\sigma^2)]}$$

$\mathrm{C}(x)$: Mean curvature at vertex v

Gaussian Weights

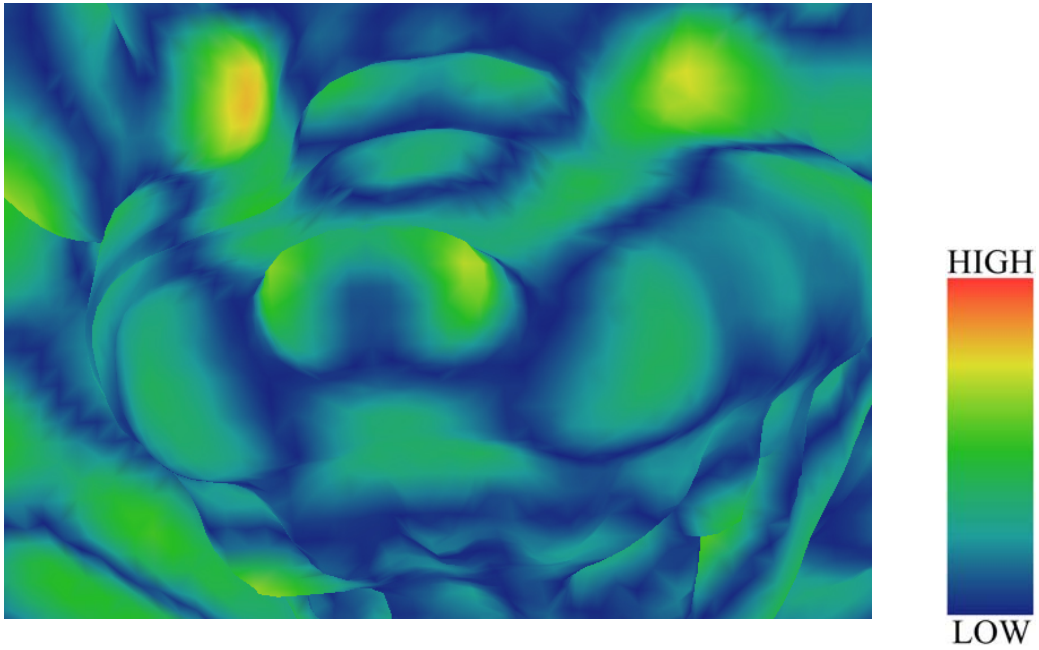


Center-Surround Operator

Saliency map at each scale i is:

$$S_i(v) = \left| G(C(v), \sigma_i) - G(C(v), 2\sigma_i) \right|$$

$$\sigma_i \in \{2\varepsilon, 3\varepsilon, 4\varepsilon, 5\varepsilon, 6\varepsilon\}, \varepsilon = 0.3\% \text{ of the diagonal of the object}$$



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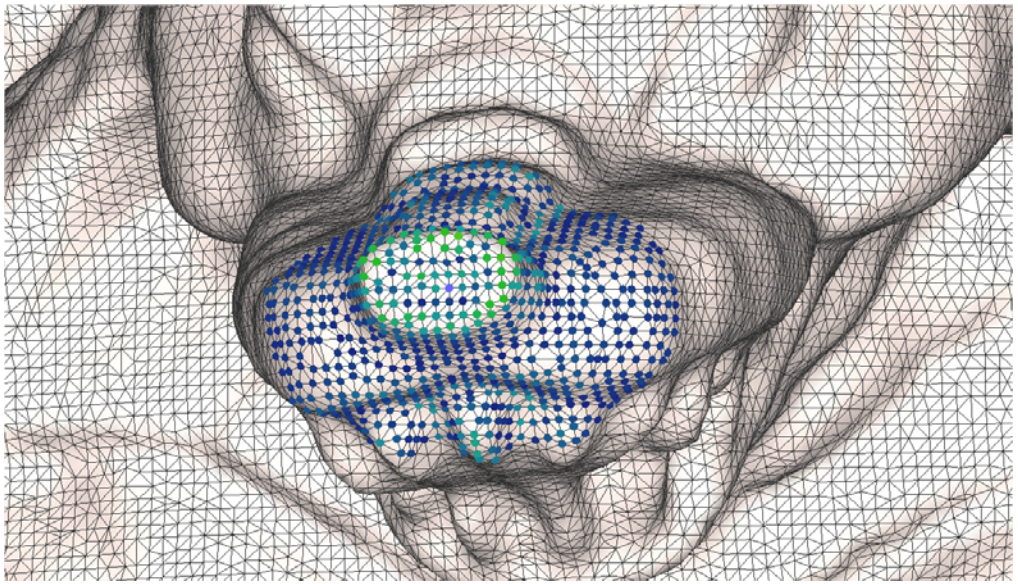
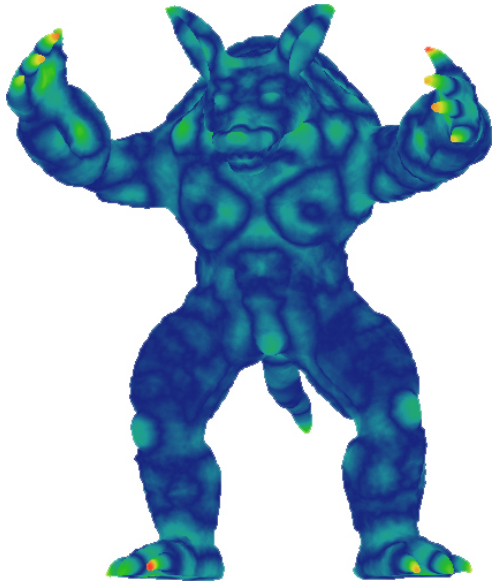
$$\sigma_i \in \{2\varepsilon, 3\varepsilon, 4\varepsilon, 5\varepsilon, 6\varepsilon\}$$

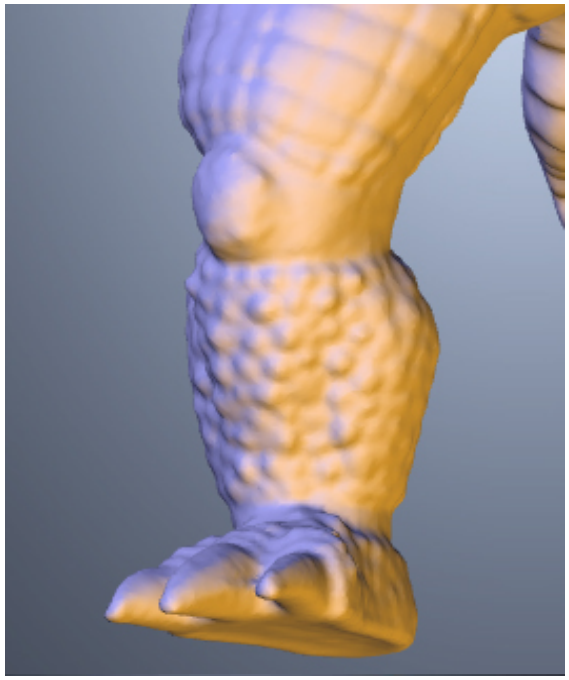
$$S_i \in \{S_0, S_1, S_2, S_3, S_4\}$$

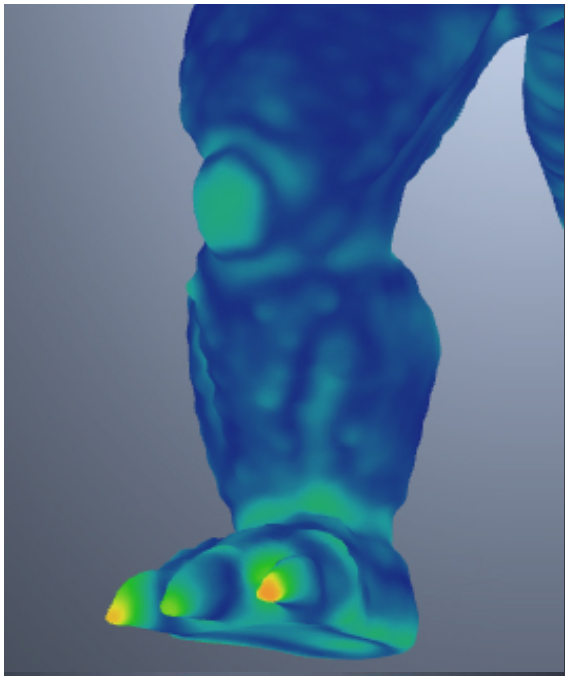
$\varepsilon = 0.3\%$ of the diagonal of the object



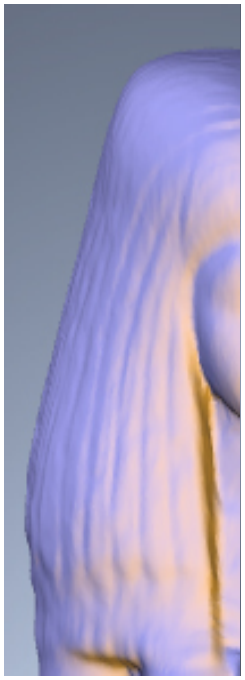


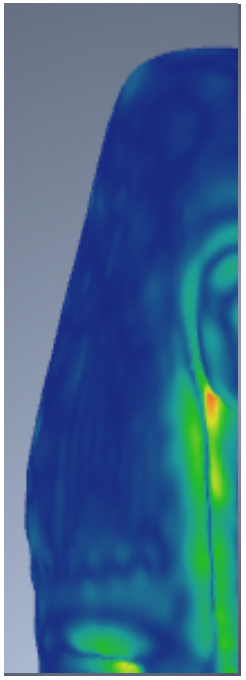
Mesh Saliency Results





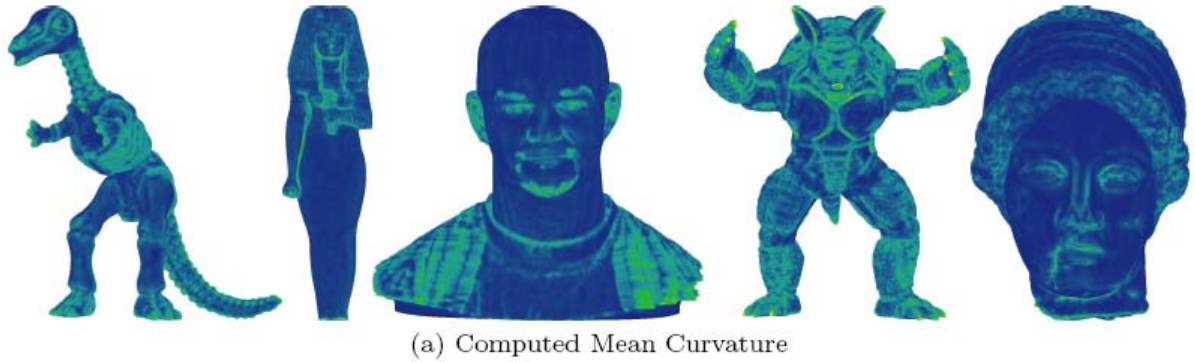
Stanford Armadillo



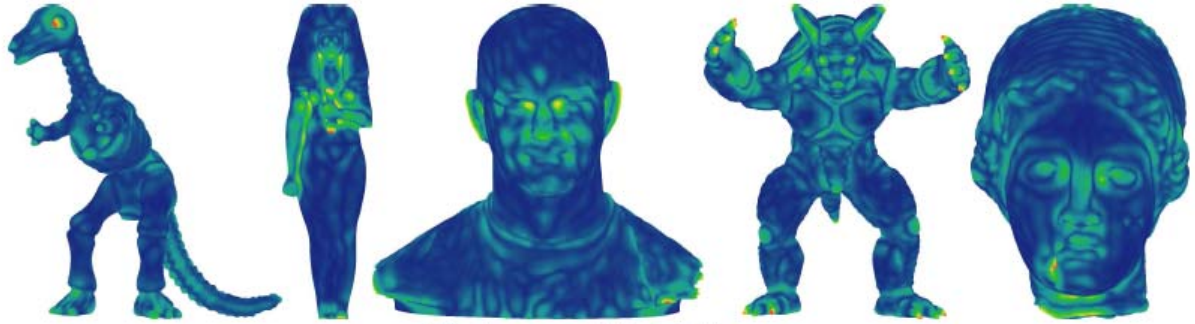


Cyberware Isis

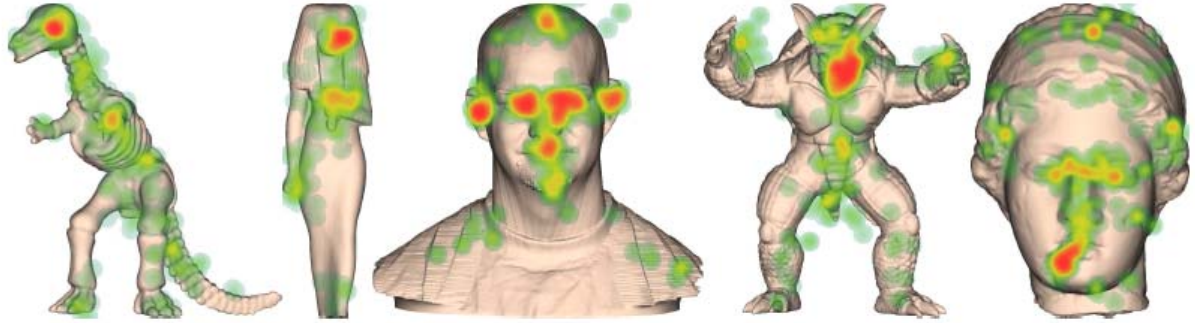
Validation of Mesh Saliency



(a) Computed Mean Curvature



(b) Computed Mesh Saliency



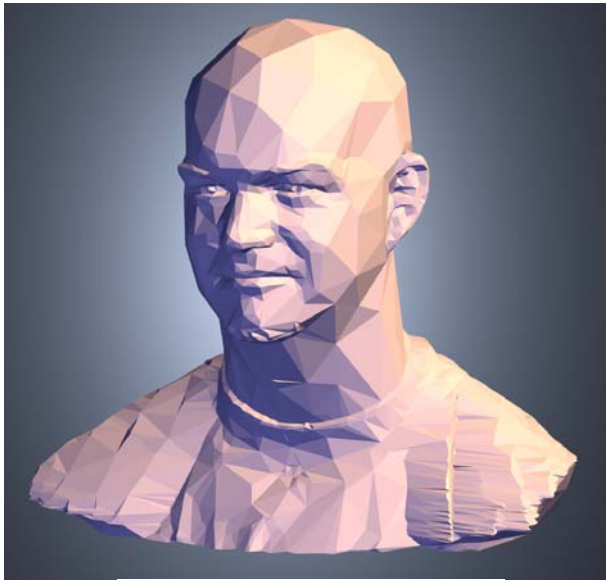
(c) Human Eye Fixations

Fixations of 18 users over first 3 seconds

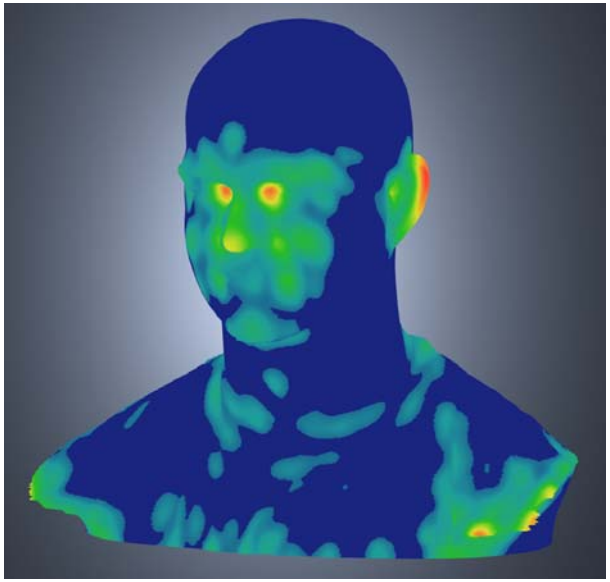
Kim, Varshney, Jacobs, Guimbretiere, ACM Transactions on Applied Perception, 2008 (under review)

Saliency Applications

Simplification: Scale the quadric error by the saliency to preserve more triangles for salient regions



Cyberware Male

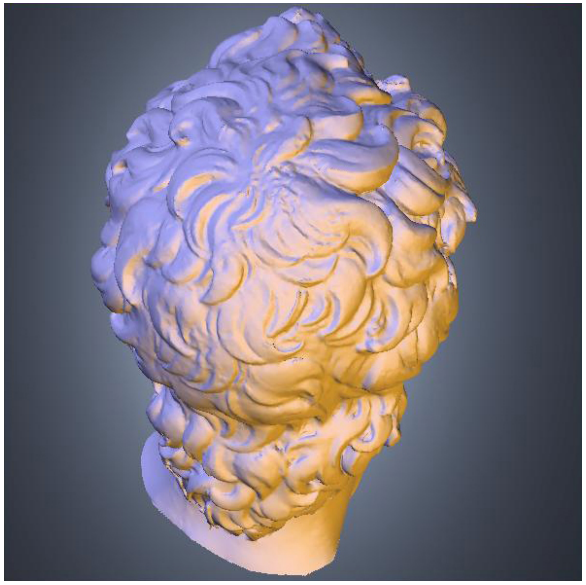


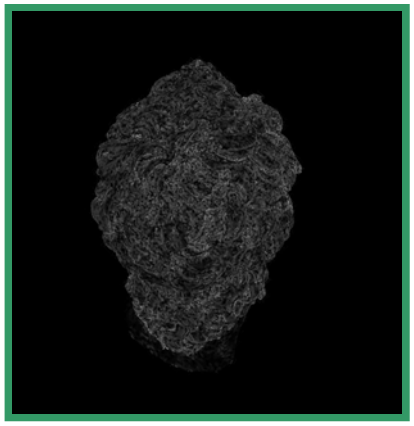
Mesh Saliency

Viewpoint Selection: Find the viewpoint that maximizes the sum of the visible saliency

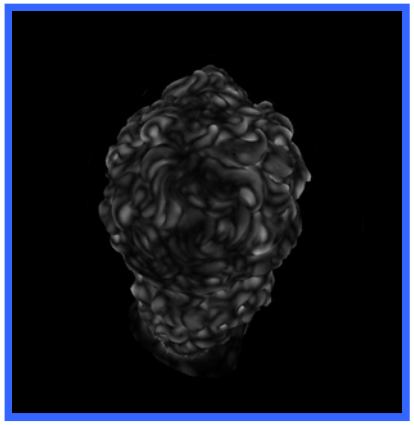
- Gradient-descent-based optimization

Viewpoint Selection

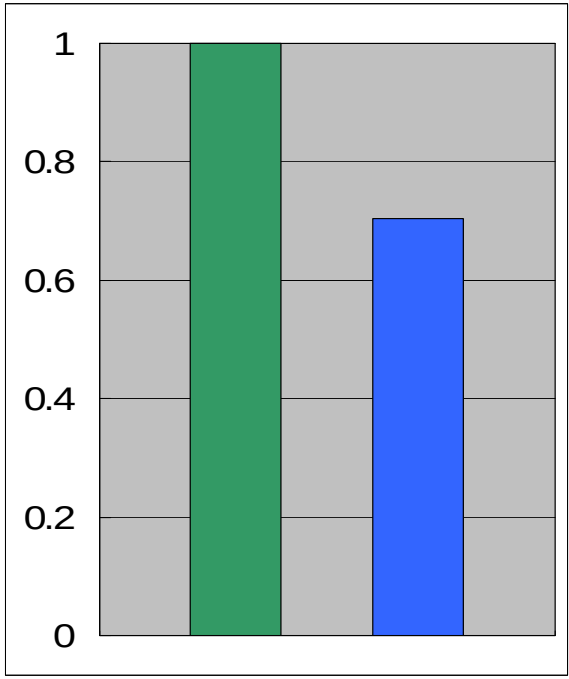




Curvature



Saliency



Preserving Salience

- ***Transfer Functions:*** Modulate opacity/transfer functions *[Groeller et al. TVCG 04 –VisSym 07]*

- ***Rendering Stylization:*** *[Kim and Varshney]*

Original

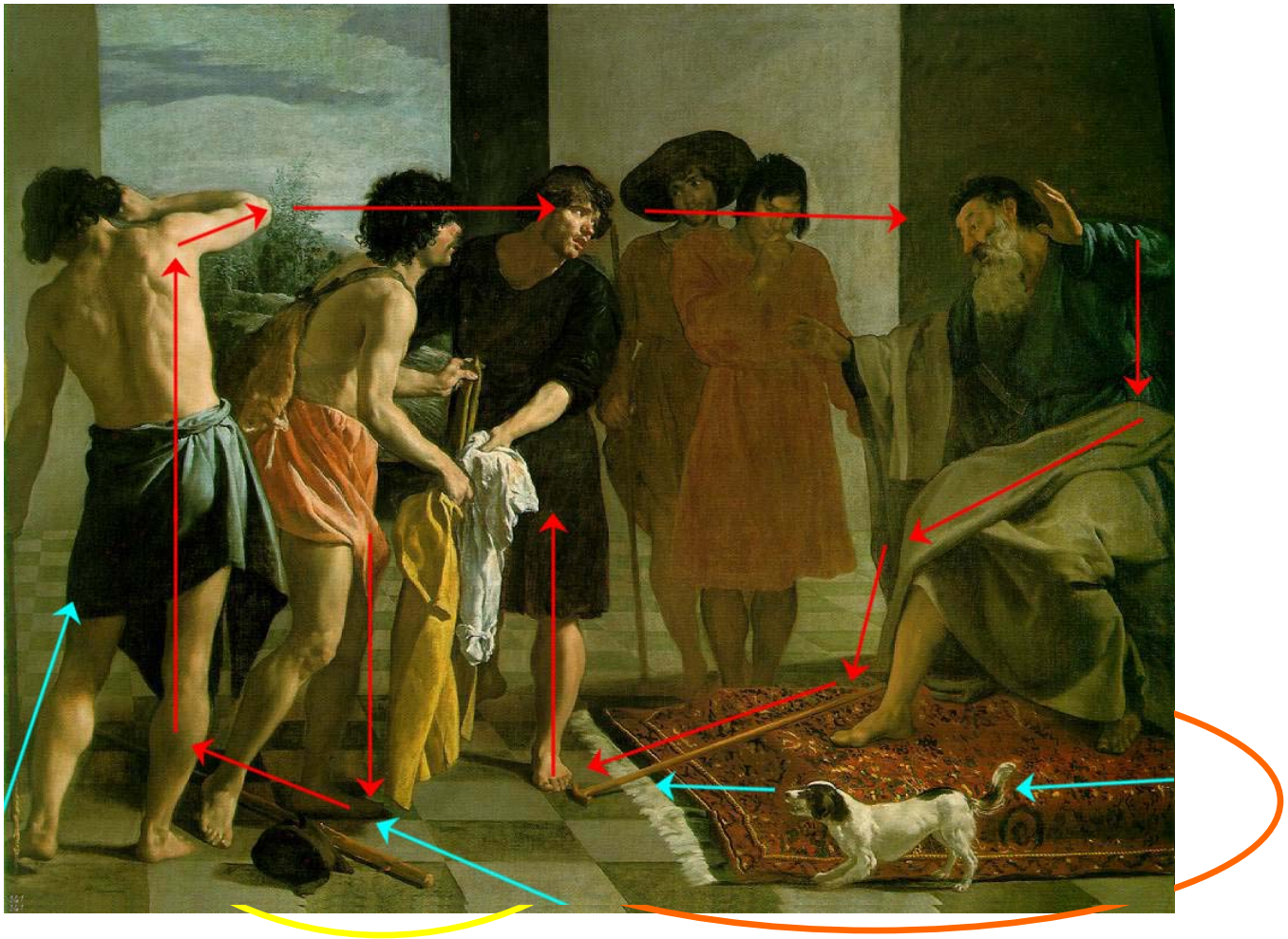
Suggestive Contours

SC weighted by Saliency

Visual Salience in Art

The Feast of Belshazzar, Rembrandt, 1635

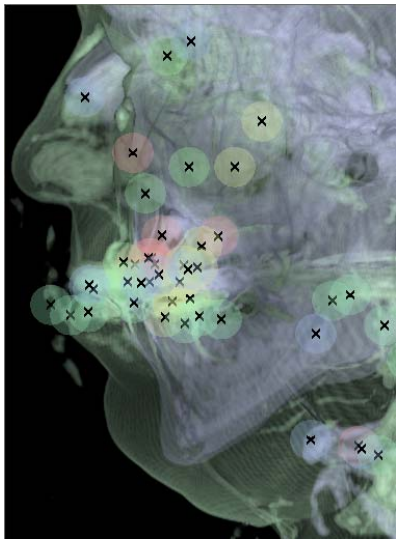
Visual Salience in Art

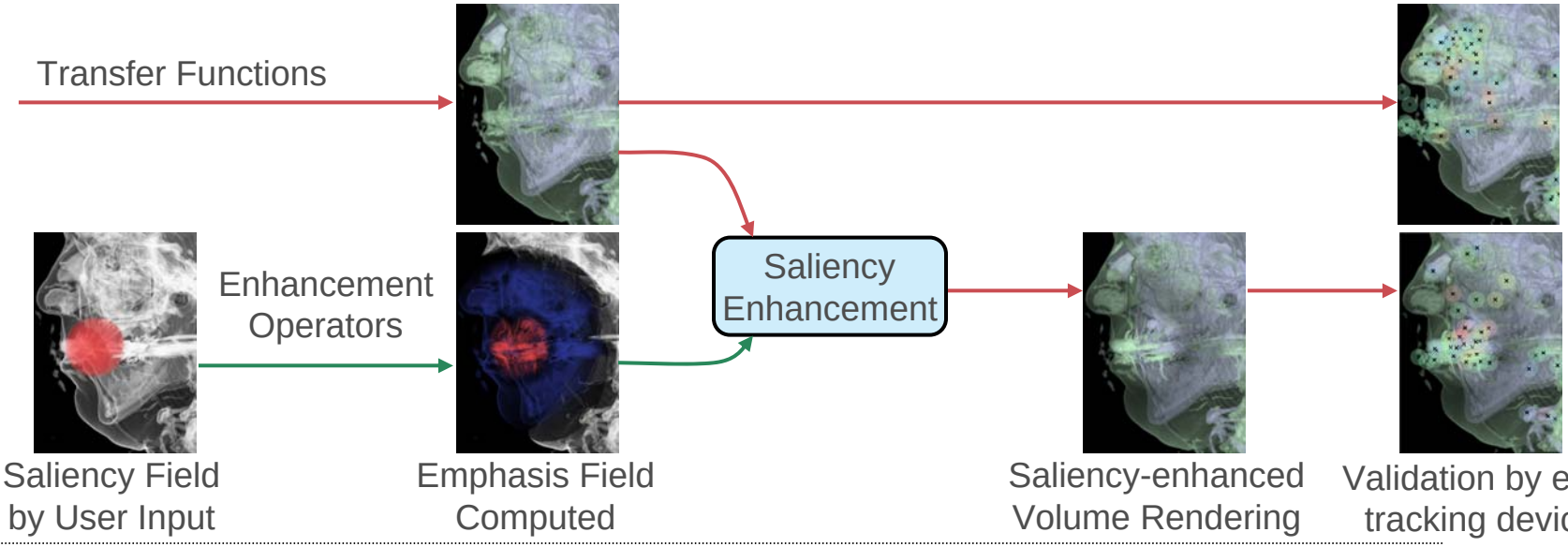


Joseph's Bloody Coat Brought to Jacob, Velasquez 1630

Salient Visualization

- Saliency Field
- Enhancement Operators
- Emphasis Field
- Saliency Enhancement
- Saliency-enhanced Volume Rendering
- Validation by eye-tracking based user study





Kim and Varshney, IEEE Visualization 2006, TVCG 2006

Emphasis Field Computation

Given a *saliency field*, can we design *some scalar field* that will generate it?

- Mesh Saliency: $\mathscr{S}(v) = G(\mathscr{C}, v, \sigma) - G(\mathscr{C}, v, 2\sigma)$

  (Unknown: $\mathscr{S}$; Known: $\mathscr{C}$, $\mathscr{C}$)
- We introduce the concept of an Emphasis Field $\mathscr{E}$ to define a Saliency Field $\mathscr{S}$ in a volume

$$\mathscr{S}(v) = G(\mathscr{E}, v, \sigma) - G(\mathscr{E}, v, 2\sigma)$$

(Known: $\mathscr{S}$; Unknown: $\mathscr{E}$, $\mathscr{E}$)

Emphasis Field Computation

- Expressible as simultaneous linear equations

$$\begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1n} \\ c_{21} & c_{22} & \cdots & c_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ c_{n1} & c_{n2} & \cdots & c_{nn} \end{bmatrix} \begin{bmatrix} \mathscr{E}(v_1) \\ \mathscr{E}(v_2) \\ \vdots \\ \mathscr{E}(v_n) \end{bmatrix} = \begin{bmatrix} \mathscr{S}(v_1) \\ \mathscr{S}(v_2) \\ \vdots \\ \mathscr{S}(v_n) \end{bmatrix}$$

  where c_{ij} is the difference between two Gaussian weights at scale σ and at scale 2σ for a voxel v_j from the center voxel v_i

- Saliency Enhancement Operator (C^{-1})

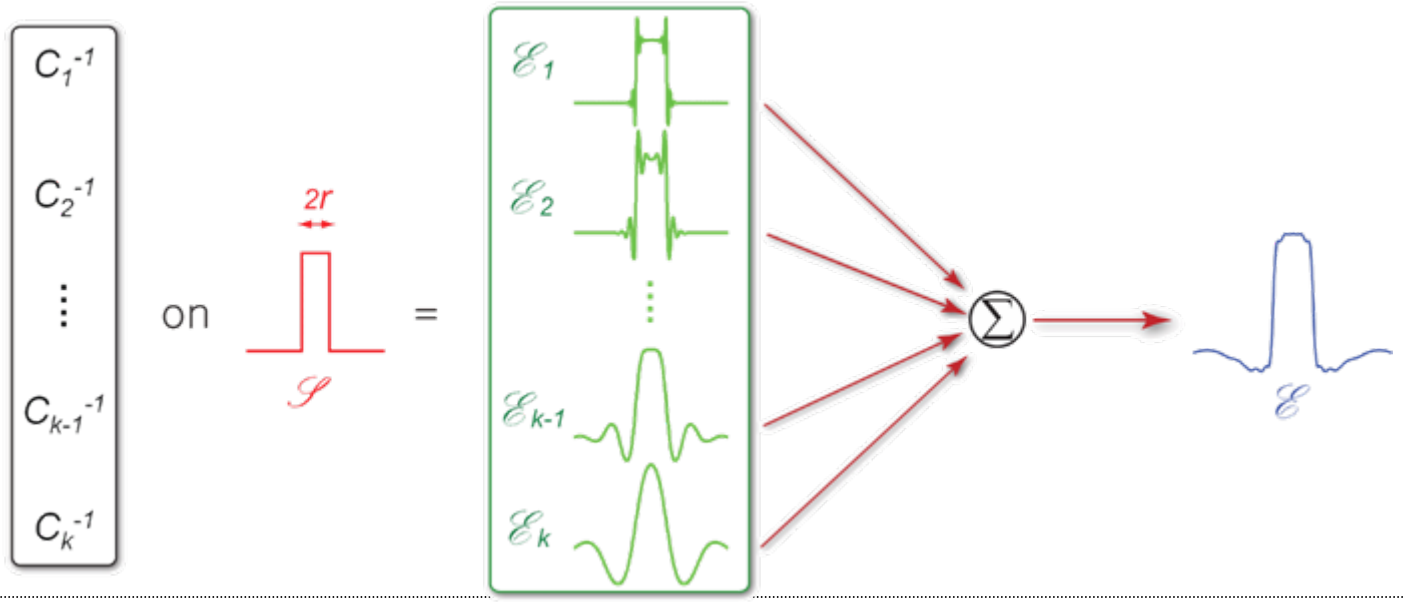
im $C^{-1}\mathscr{S}$

y ne enhancement operator C^{-1}

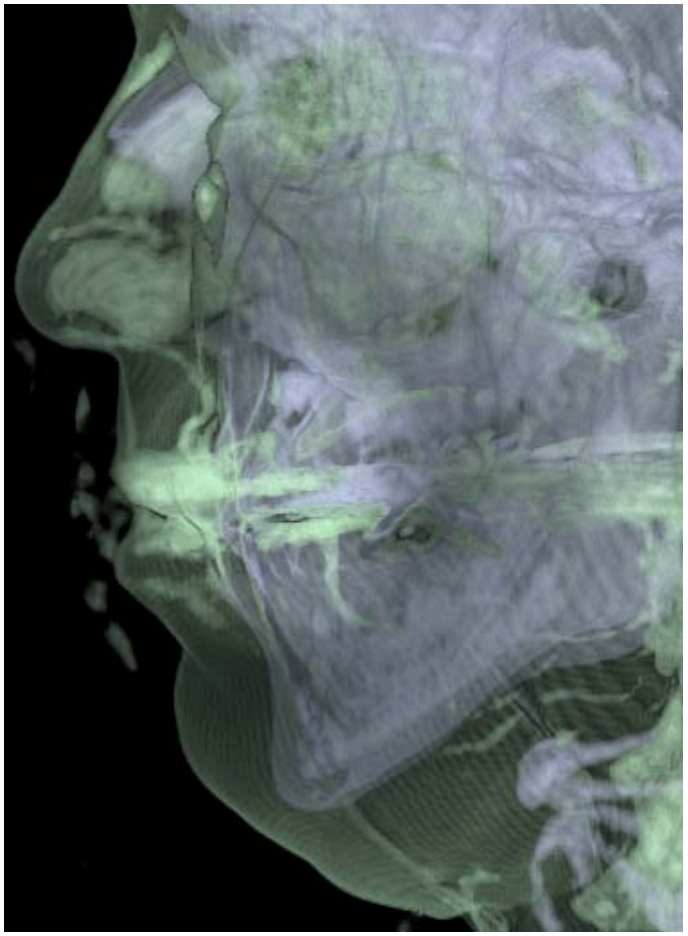
e field $\mathscr{E}$

Emphasis Field Computation

- We like to use enhancement operators at multiple scales σ_i
  - Let $\mathscr{E}_i$ be the emphasis field at scale σ_i
  - Compute this by applying the enhancement operator C_i^{-1} on the saliency field $\mathscr{S}$
  - Final emphasis field is computed as the summation of $\mathscr{E}_i$



Salient Visualization - Brightness



Traditional Volume Rendering

Saliency-based Enhancement

Traditional Volume Rendering

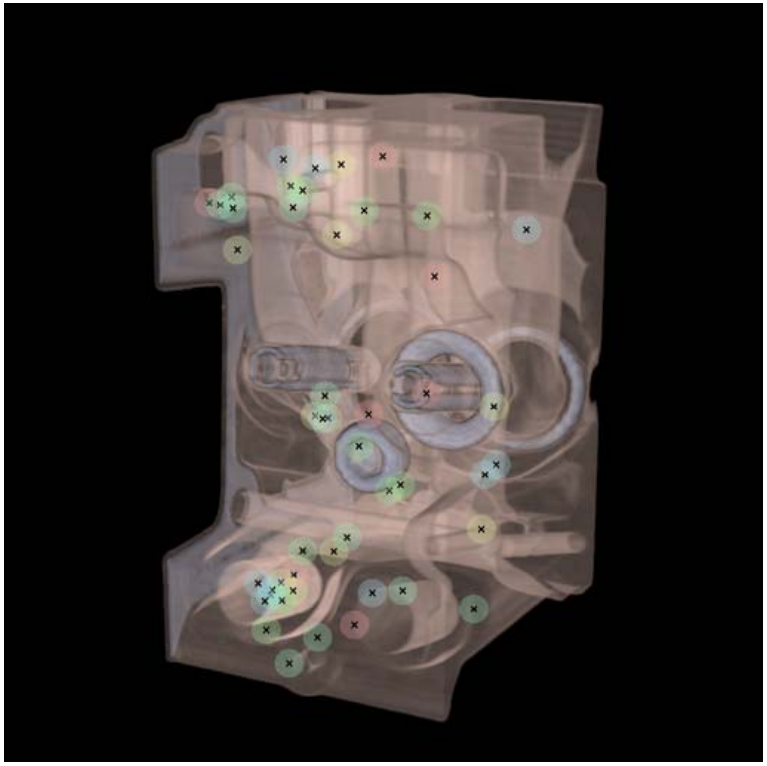
Saliency-based Enhancement

User Study

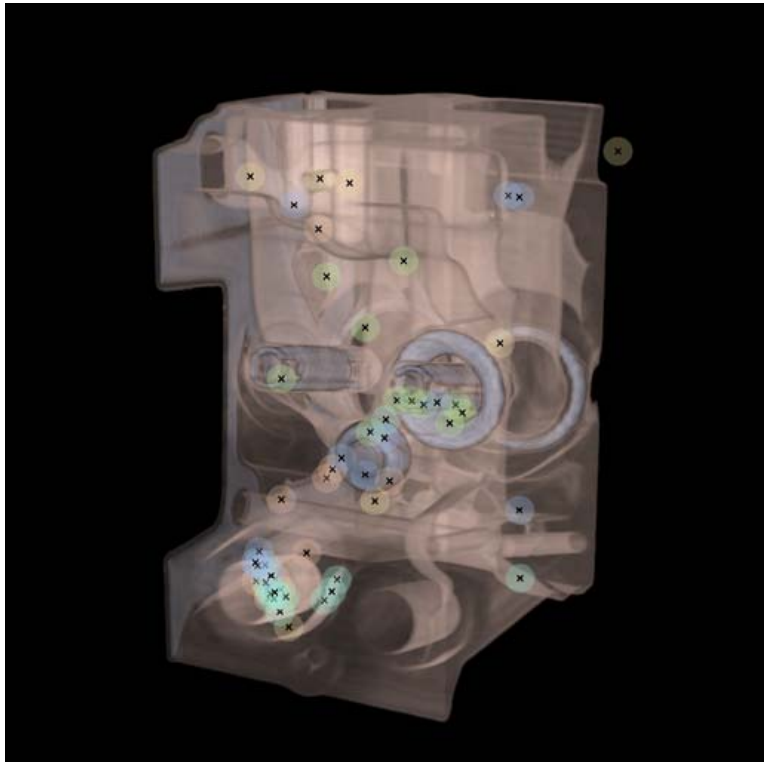
- Validated results by an eye-tracking-based user study
- Eye-tracker ISCAN ETL-500
  - Records eye movements at 60Hz

- Hypotheses: *The eye fixations increase over the region of interest (ROI) in a volume by the saliency-guided enhancement compared to*
  - the traditional volume visualization *(Hypothesis H1)*
  - the Gaussian-based enhancement *(Hypothesis H2)*

User Study – Result I



Gaussian Blurred Emphasis With Fixation Points



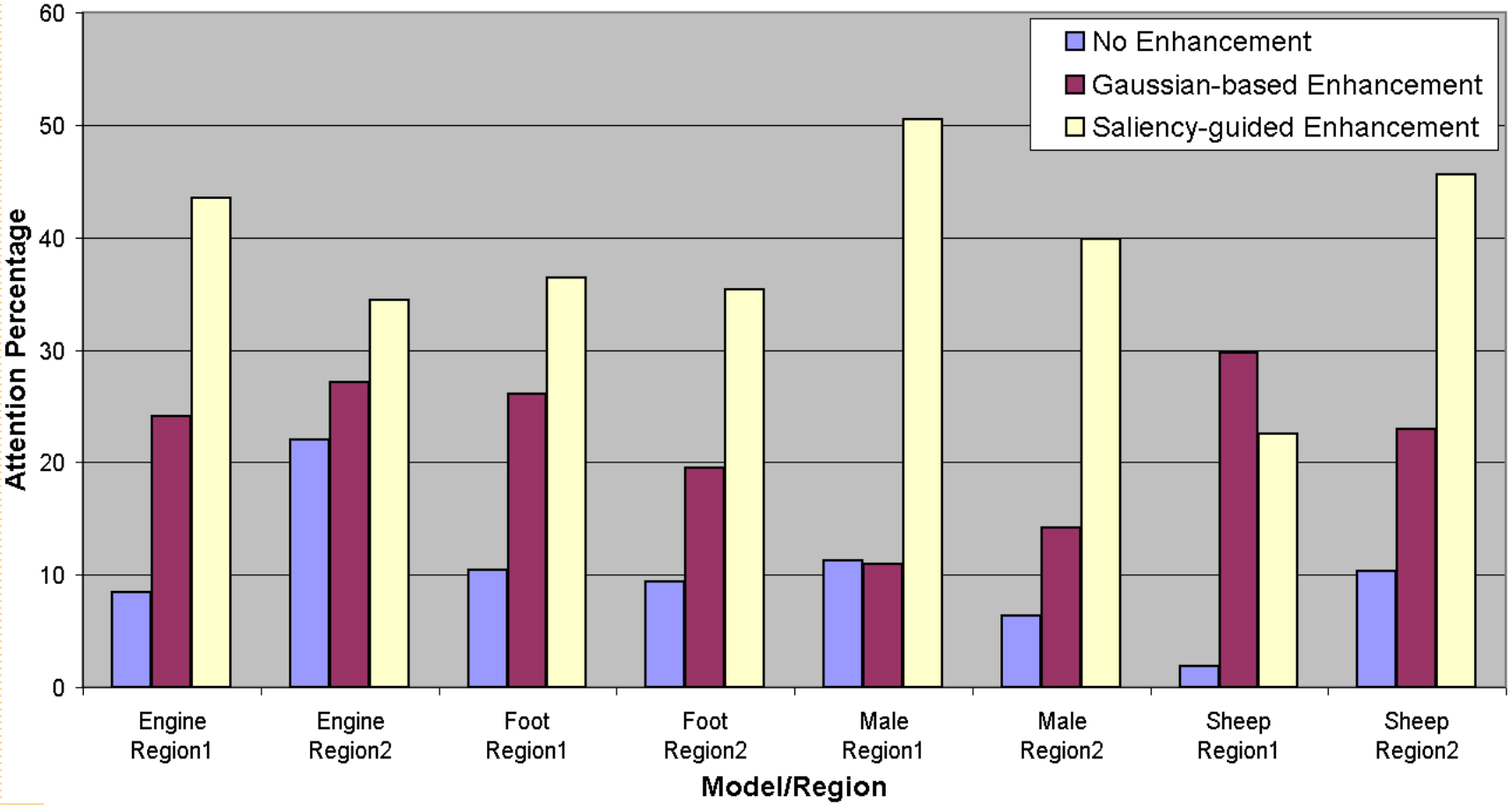
Saliency-guided Enhancement With Fixation Points

User Study – Result II

Saliency-guided Enhancement
With Fixation Points

Gaussian-based Enhancement
With Fixation Points

Data Analysis

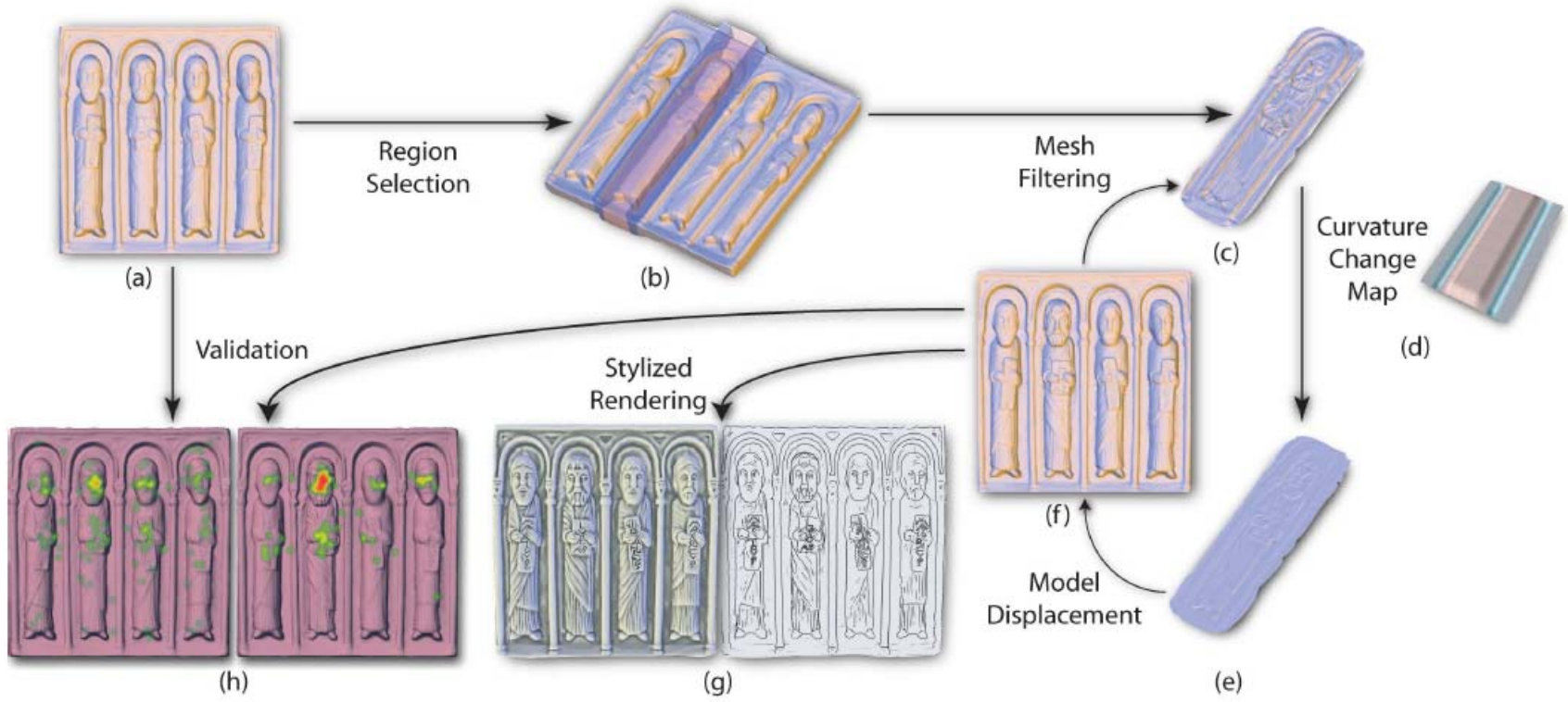


The percentage of fixations on the ROI for the original, Gaussian-enhanced, and Saliency-enhanced visualizations

Salient Visualization: Geometry

- Seen the use of luminance, chrominance, texture, …
- Can geometry be altered to draw visual attention?
- Advantages:
  - Complementary to others
  - Earliest in the visual computing pipeline
  - View-independent effects
  - Rendering Stylizations

Salient Visualization: Geometry



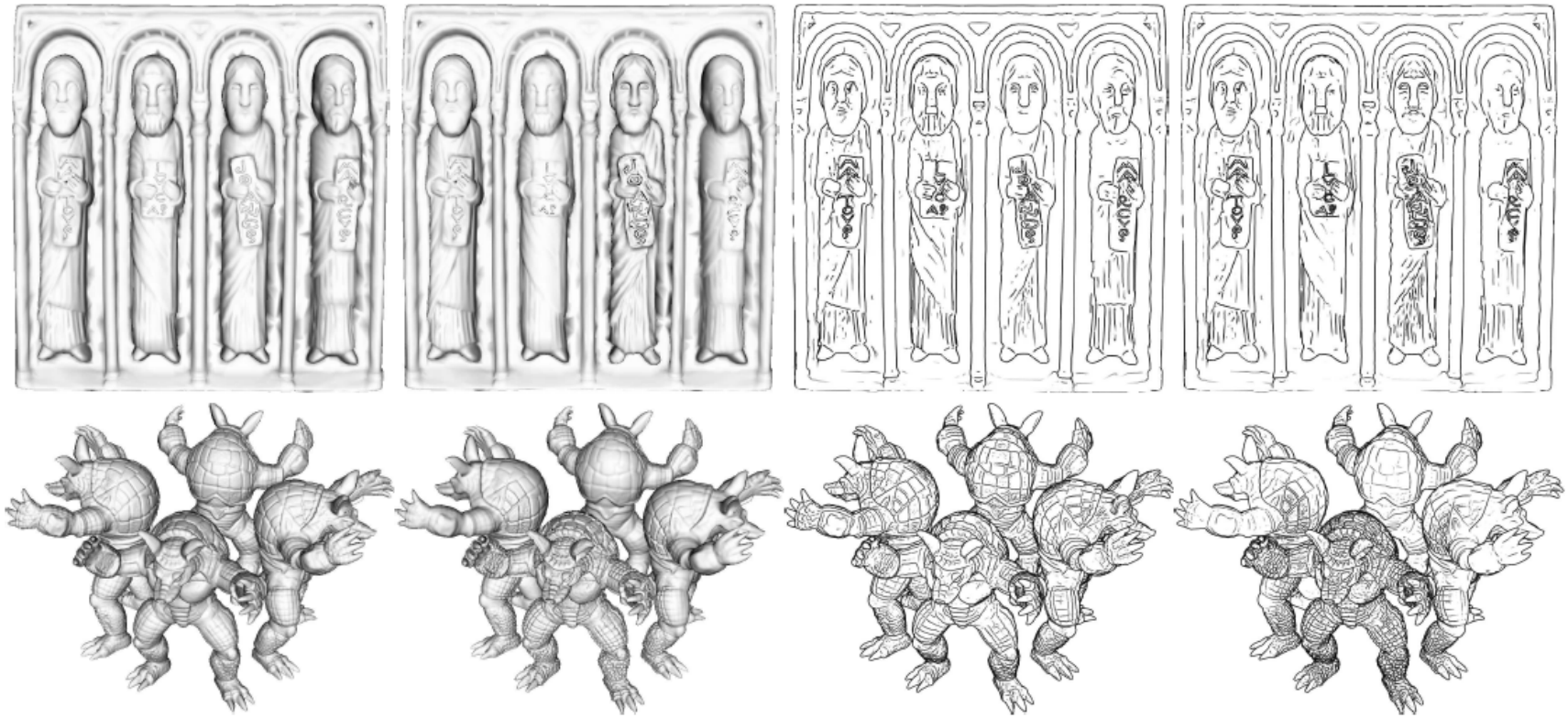
Persuading Visual Attention through Geometry, Kim and Varshney, IEEE TVCG, June 2008

Salient Visualization: Geometry

Original

Altered

Rendering Stylizations



Persuading Visual Attention through Geometry, Kim and Varshney, IEEE Transactions on Visualization and Computer Graphics, June 2008

Concluding Remarks

- Computational models that mimic perceptual salience for 3D objects
- Data is always sacrosanct but visualization is never neutral
  - View location, view orientation, lighting (number, and types), reflectance, transfer functions, …
- Every communication has a message
  - Whether intentional or not
- Methods to identify, preserve, and enhance visual saliency

Salient Visualization

- Define Salient
  - Human
  - AI assistant
- Compute Data Salience
  - Features
  - Patterns
  - Coherence
  - Interactions
- Preserve and Enhance it through the Visual Computing pipeline:
  - Camera
  - Geometry / Data Representation
  - Transfer Functions
  - Lighting
  - Texture, Color, Glyphs
- Validate in final rendering

Concluding Remarks

- Every communication genre employs its distinct rhetorics
  - Movies vs documentaries
  - Posters vs newspapers
  - Photography vs art
- Towards a *Language of 3D Visual Communication*
  - Data: nouns
  - Visual Salience: adjectives
  - Guiding Visual Attention: verbs
- Could be the beginnings of a new and rich genre of visual communication

Or it could go the way of personal air cars …

Acknowledgements

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IARPA

Communication – Language vs Visual

- ***Language:*** linear, apprehended slowly, systematic processing

- ***Images:*** Comprehended wholistically, instantaneously, emotional processing

- Images (or image-evoking language) are powerful, precisely because they provide superior opportunities to dominate the *field of consciousness*

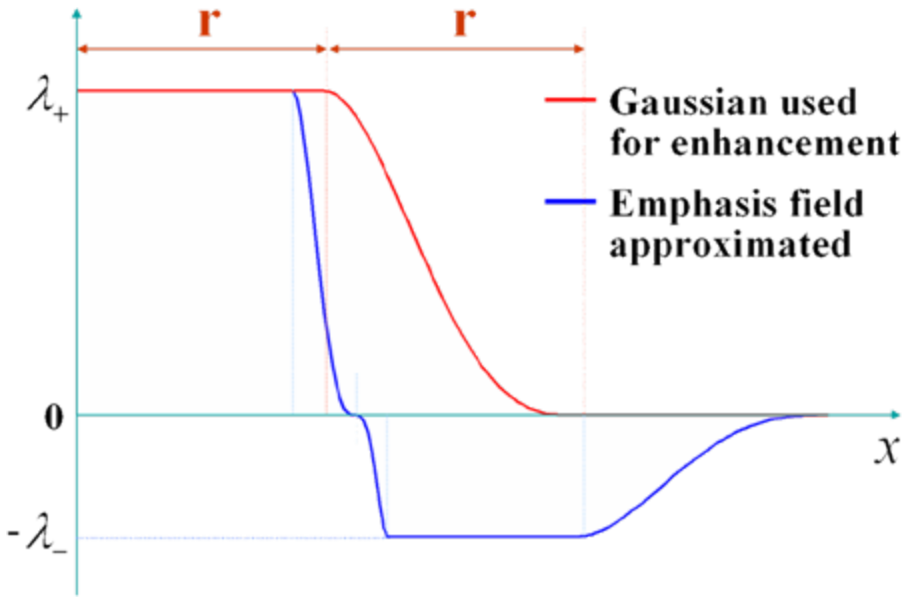
Emphasis Field in Practice

- A system of simultaneous linear equations in n variables
  - Generally, can handle arbitrary saliency regions and values
  - Computationally expensive: $O(kn^2)$ or $O(n^3)$
- Alleviate this by solving a 1D system of equations
  - Given a saliency field
  - Solve 1D system of equation multiple scales and sum ther
  - Approximate results using piecewise polynomial radial functions [Wendland 1995]

- Interpret results to be along the radial dimension
  - Assume spherical regions of interest (ROI)

Saliency-guided Enhancement

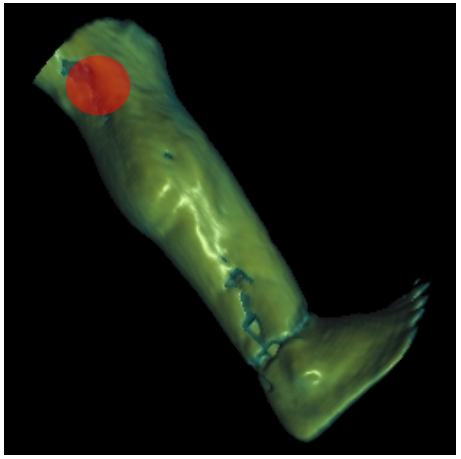
- Previous Gaussian-based Enhancement of a Volume
  - Volume Illustration [Rheingans and Ebert TVCG 01]
  - Importance-based regional enhancement



- Various rendering stylizations and effects possible
  - Brightness
  - Saturation

Preserving Salience

- Draw viewer attention in several ways
- Obtrusive methods like arrows or flashing pixels



  - Distracts the viewer from exploring other regions
- Principles of *visual perception* used by artists and illustrators
  - Gently guide to regions that they wished to emphasize